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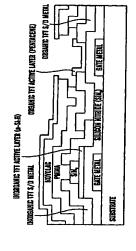


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(71) Applicant (for all derignated States except US): OPTICOM ASA [NONO]; P.O. Box 1872 Vila, N-0124 Oslo (NO).	(NO).	R, GB, GR, IE, IT, LU, MC, NL, PT, SB, OAPI parent (BF, BI, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).
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(54) THE: INTEGRATED INORGANIC/ORGANIC COMPLEMENTARY THIN-FILM TRANSISTOR CIRCUIT

(74) Agent: LEISTAD, Geirt, I.; Opticom ASA, P.O. Box 1872 Vika, N-0124 Oslo (NO).



(57) Abstract

An integrated organio/inorganic complementary thin-film transistor circuit comprises a first and a second transistor which are operatively connected on a common authorist, wherein the first transistor is an inorganic thin-film transistor and the second an organic of vice versa. Each of the transistors has a separate gate electrode and the organic earlies enriched mentation is an o-channel transistor mad be expected mentation in the organic described and the organic earlies enriched mentation is in the case of a p-channel semiconductor material is in the case of a p-channel at transistor the organic electrode are deposited from the inorganic material is in the case of a p-channel at transistor deviate of the language electrodes are deposited from the same layer level in the thin-film students of the source thin-film transistor and the case the organic extire semiconductor material is no organic n-channel transistor, and the organic extire semiconductor material in an organic p-channel transistor, and the organic extire semiconductor material in an organic n-channel transistor of the organic extire extincted during the inorganic n-channel transistor and in a more specific method for fabricating a complementary transistor circuit the inorganic active semiconductor material in an organic n-channel transistor of a silicon material is putterned and that the personned drain areas in the organic transistor. A laye of penatecon is deposited over an isolated electrically from the inorganic chirc-film transistor is isolated electrically from

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Integrated inorganic/organic complementary thin-film transistor circuit.

thin-film transistor circuit, comprising a first and a second transistor which is operatively connected and provided on a common substrate, wherein the first transistor is an inorganic thin-film transistor and the second transistor an The invention concerns an integrated inorganic/organic complementary organic thin-film transistor. and wherein the complementary thin-film transistor circuit forms a multilayer structure.

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first and a second transistor which are operatively connected and provided on thin-film structure with successively deposited and patterned thin-film layers. inorganic/organic complementary thin-film transistor circuit, comprising a The present invention also concerns methods for fabricating an integrated wherein the complementary thin-film transistor circuit forms a multilaver a common substrate. wherein the first transistor is an inorganic thin-film transistor and the second transistor an organic thin-film transistor, and

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electronic products, as they can provide very low static power dissipation for applications such as microprocessors. But complementary circuits may also be of interest for more general application. e.g. in portable battery-operated complementary integrated thin-film circuits with sufficient performance for semiconductors dominate the markets for a number of microelectronic Integrated circuits of silicon realized as complementary metal-oxide digital circuits. It has, however, turned out to be difficult to realize commercial applications. 15

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Hydrogenated thin-film transistors of silicon (a-Si:H TFT) have found a new with active matrix. However, complementary a-Si:H circuits are problematic, sabricated and with performance comparable to that which can be obtained application in thin-film components, particularly in liquid crystal displays transport mobility. Recently TFTs with organic active layers have been as the hole transport mobility typically is much lower than the electron with amorphous silicon devices (a-Si:H devices).

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For instance there is in US patent no. 5 347 144 (Garnier & al.) disclosed a thin-film field-effect transistor with an MIS structure which includes a thin semiconductor layer contacts a surface of a thin-film made of isolating semiconductor layer between the source and drain electrode. The thin material which at its second surface contacts a conducting grid. The

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semiconductor is made of at least one polyconjugated organic compound with hydrocarbons and among these polyacenes. The transistor of Garnier & al. is a determined molecular weight. As organic semiconductor material Garnier stated to be particularly suited as a switching or amplifying device. & al. among others mention different various aromatic polycyclic

properties. Further attempts have been made building complementary circuits with combinations of inorganic and organic devices on separate substrates Also simple organic complementary thin-film transistor circuits have been discussed in the literature, but have not shown the desired performance

and with external connection.

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complementary circuit with an inorganic n-channel thin-film transistor and an In US patent no. 5 625 199 (Baumbach & al.) there is, however, disclosed a organic p-channel thin-film transistor. The n-channel thin-film transistor employs hydrogenated amorphous silicon as active material and the

ransistor circuit according to Baumbach & al. can be used for implementing p-channel of the organic thin-film transistor employs α -hexathienylene (a-6T) as active semiconductor material. The complementary thin-film an integrated complementary inverter or other complementary circuits. 13

electrodes on both sides of the organic semiconductor layer, something which disadvantages both from a processual point of view as well as with regard to according to Baumbach & al. is, however. encumbered with a number of Baumbach & al. propose to provide respectively the source and drain The integrated complementary inorganic/organic thin-film transistor general application in more comprehensive transistor circuits. Thus 2

firstly is not necessary and additionally comports a number of disadvantages difficult to pattern contacts on the top of the organic semiconductor unless hin-film transistor must be formed in different steps and it will also be in the fabrication. Further the source and drain contacts of the organic shadow masks are used. 2

according to Baumbach & al, it is probable that an undesirable large leakage Nor has the complementary thin-film transistor according to Baumbach an isolated organic semiconductor material in the organic thin film transistor. As it will be desirable to be able to turn the inorganic transistor on and to urn the organic transistor off or vice versa using potential with the same sign, this may be problematic. In the complementary thin-film transistor 3 35

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of organic materials which may be used for forming active semiconductors of materials proposed. It is. however, evident from Baumbach & al. that the use will be problematic if the complementary thin-film transistor shall be used in Another disadvantage of the complementary thin-film transistor according to n-channel and the p-channel transistor. More complex transistor circuits built complex circuits. An inverter realized according to Baumbach & al. switches the n-type demands relatively complicated and costly fabricating processes from complementary devices shall require that common electrodes are not used in these. Even in simple inverters a common gate electrode will give complementary thin-film transistor according to Baumbach & al. uses the as stated in the cited US patent at about 5V at a supply voltage of 7,2 V. inorganic transistor as n-channel transistor and the organic transistor as p-channel transistor, something which is understandable in light of the Baumbach & al. is that a common gate electrode is used both for the increased stray capacitance. Further it shall be remarked that the and hence is not easy to realize for the time being.

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A first object of the present invention is hence to overcome the disadvantages and simultaneously have low static power consumption, such that they can be complementary inorganic/organic thin-film transistor circuit which is suited complementary thin-film transistor circuits which allow a cheap fabrication which are connected with prior art and particularly to provide an integrated for use in large transistor circuits. Another object is to provide used in portable battery-operated equipment.

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inorganic/organic thin-film transistor circuits and this in as few process steps whereby it particularly shall be possible to realize the inorganic transistor as an n-channel transistor and the organic transistor as a p-channel transistor or A further object of the present invention is to provide an uncomplicated and as possible, while a device with good electric properties is obtained and inexpensive method for fabricating integrated complementary vice versa. 2 25

inorganic/organic complementary thin-film transistor circuit which according to the invention is characterized in that the organic thin-film transistor is an n-channel transistor and that the organic thin-film transistor is a p-channel transistor, or vice versa, the organic active transistor material in each case The above-mentioned and other objects are achieved with an integrated

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provided for each of the transistors, that the organic active semiconductor in an organic p-channel transistor in each case is provided electrically isolated n-channel organic semiconductor material, that separate gate electrodes are semiconductor in an organic n-channel transistor optionally is provided being respectively a p-channel organic semiconductor material or an from the inorganic n-channel transistor, and that the organic active electrically isolated from the inorganic p-channel transistor.

cadmium selenide (CdSe), cadmium telluride (CdTe), or composite inorganic single crystal silicon. copper-doped polycrystalline germanium (pc-Ge:Cu), According to the invention the inorganic active semiconductor material is advantageously selected among hydrogenated amorphous silicon (a-Si:H), hydrogenated or unhydrogenated microcrystalline silicon (µc-Si:H;µc-Si), nydrogenated or unhydrogenated polycrystalline silicon (pc-Si:H;pc-Si), emiconductors based on said materials, possibly in single crystal form. 2

naterial, particularly p-channel hydrogenated amorphous silicon (a-Si:H) inorganic active semiconductor material is preferably a p-channel silicon (a-Si:H), and where the inorganic transistor is a p-channel transistor, the inorganic active semiconductor material is preferably amorphous silicon Where the inorganic thin-film transistor is an n-channel transistor, the 2

polyconjugated organic compound or compounds are selected selected among compound with a specific molecular weight. It is then advantageous that the inorganic thin-film transistor comprises at least one polyconjugated organic n an advantageous embodiment the active semiconductor material in the conjugated oligomers, polycyclic aromatic hydrocarbons, particularly 20

polyacenes, or polyenes. 25

advantageous that the organic active semiconductor material is pentacene, and where the organic thin-film transistor is an n-channel transistor, it is advantageous that the organic active semiconductor material is copper Where the organic thin-film transistor is a p-channel transistor, it is hexadecafluorophtalocyanide.

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source electrode and the drain electrode of the organic thin-film transistor is provided in one and the same level in the thin-film structure of the organic Finally, it is according to the invention particularly advantageous that the hin-film transistor.

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A first method for fabricating an integrated inorganic/organic complementary organic thin-film transistor on the same level in the thin-film structure of the p-channel organic active semiconductor material or correspondingly forming isolated from the inorganic n-channel transistor and optionally providing the n-channel organic active semiconductor material and a p-channel inorganic forming the inorganic thin-film transistor as an n-channel transistor and the the organic thin-film transistor as an n-channel transistor and the inorganic thin-film transistor as a p-channel transistor by depositing respectively an depositing material for the source electrode and the drain electrode of the organic active semiconductive material in an organic n-channel transistor organic thin-film transistor and in each case providing the organic active respectively an n-channel inorganic active semiconductor material and a thin film transistor circuit is according to the invention characterized by active semiconductor material, depositing separate gate electrodes for respectively the first and the second transistor on a common substrate, semiconductor material in an organic p-channel transistor electrically organic thin-film transistor as a p-channel transistor by depositing electrically isolated from the inorganic p-channel transistor.

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electrodes of the first transistor in form of a second metal over the source and nydrogenated polycrystalline silicon (n*pc-Si:H) as source and drain contacts the whole organic thin-film transistor and patterning this such that the source characterized by comprising steps for depositing separate gate electrodes of a gate electrode, depositing an inorganic active semiconductor in the form of ayer level in the thin-film structure, forming an isolating double layer over electrodes for the second transistor in the form of a third metal in the same hydrogenated amorphous silicon (a-Si:H) above one of the gate electrodes and drain electrodes and the gate isolator in the second transistor become which thus forms the gate electrode of the first transistor, depositing and exposed, whereafter a layer of pentacene is deposited above the isolating depositing separate inorganic isolators of silicon nitride (SiN_x) over each complementary thin-film transistor circuit is according to the invention patterning an n⁺ doped layer of either hydrogenated amorphous silicon drain contacts thereof, depositing and patterning the source and drain for the first transistor, depositing and patterning the source and drain (n^a-Si:H) or hydrogenated microcrystalline silicon (n^ μ c-Si:H) or first metal for each of the two transistors on a common substrate, A second method for fabricating an integrated inorganic/organic 25 3 35 2

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layer in the exposed portion forming the active semiconductor material of the double layer and the exposed portion of the second transistor, the pentacene organic thin-film transistor and being provided electrically isolated against the additional pentacene layer broken by a re-entrant edge of the profile of the isolating double layer.

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realized in a tri-layer process which forms an inverted staggered three-layer In an advantageous embodiment of the last-mentioned method according to the invention the steps for forming the inorganic thin-film transistor are

In another advantageous embodiment of the last-mentioned method according to the invention the steps for forming the inorganic thin-film transistor are realized in a back-channel etch process. 2

In an advantageous embodiment of the last-mentioned method according to double layer of polymethylmetacrylate (PMMA) and Novolac photoresist. organic thin-film transistor is isolated by a re-entrant profile of a broken the invention the active semiconductor in the form of pentacene in the 2

In an advantageous embodiment of the last-mentioned method according to the invention gold is evaporated thermally for forming the source and drain electrodes of the organic thin-film transistor.

Finally, the pentacene layer which is deposited over the isolating double layer can optionally be removed. 20

exemplary embodiments and with reference to the accompanying drawings The invention shall now be explained in more detail in connection with wherein fig. I shows a complementary thin-film transistor circuit according to prior art as exemplified by the above-mentioned US patent No. 5 675 199, 22

fig. 2a a first embodiment of the complementary thin-film transistor circuit according to the invention, fig. 2b a second embodiment of a complementary thin-film transistor circuit according to the invention,

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fig. 2c a variant of the embodiment in fig. 2b,

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fig. 3a a third embodiment of the complementary thin-film transistor circuit according to the invention.

fig. 3b a fourth embodiment of the complementary thin-film transistor circuit according to the invention.

5 fig. 3c a fifth embodiment of the complementary thin-film transistor circuit according to the invention.

fig. 3d a variant of the embodiment in fig. fig. 3c,

figs. 4a-4r schematically the process steps in an embodiment of a method according to the present invention,

10 figs. 5a-5d a tri-layer etch process as used with a method according to the present invention.

figs. 6a-6c a back-channel etch process as used with a method according to the present invention.

the present invention.

fig. 7a schematically a section through an inverter realized with the complementary thin-film transistor circuit according to the present invention,

fig. 7b the circuit diagram of the inverter in fig. 7a.

fig. 7c a line drawing based on a microphotograph of the actual inverter in fig. 7a realized in thin film technology.

fig. 8a the voltage transfer curve for an inverter realized as in fig. 7a,

20 fig. 8b a diagram of the transient current for an inverter realized as in fig. 7a,

fig. 9a a line drawing based on a microphotograph of an actual NAND gate realized with complementary thin-film transistor circuits according to the present invention,

fig. 9b a circuit diagram of the NAND gate in fig. 9a,

25 fig. 9c the output voltage of the NAND gate in fig. 9a,

fig. 10 a line drawing based on a microphotograph of an actual five-stage ring oscillator realized with complementary thin-film transistor circuits according to the present invention,

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ig. 11 the circuit diagram of the ring oscillator in fig. 10,

figs. 12a-12c respectively the gate delay, the power dissipation and the power dissipation product for the ring oscillator in fig. 10 as function of the supply voltage and

figs. 13a-c respectively the gate delay, the power dissipation and the power dissipation product as function of the supply voltage for an eleven-stage ring oscillator realized with complementary thin-film transistor circuits according to the present invention.

First there shall now be given a discussion of prior art with the

above-mentioned US patent No. 5 625 199 (Baumbach & al.) as starting point. Therein is disclosed a complementary circuit with inorganic n-channel thin-film transistor and an organic p-channel thin-film transistor, such as rendered in fig. 1. For both transistors a common gate electrode 2 of metal is provided on a substrate 1. Over the gate electrode is provided a dielectric 3 which forms the gate isolator and which typically is made of a

which forms the gate isolator and which typically is made of a non-conducting polymer. Over the gate isolator 3 then follows a layer 4 of undoped amorphous silicon which forms the active layer of the inorganic n-channel transistor. On the a-Si layer 4 is provided a patterned isolation layer 5 which serves to prevent short circuit between the source and drain

areas of the n-channel transistor. Over the layers 3, 4 and 5 a further layer 6 of n⁺ amorphous silicon has been deposited and provides electrical contact to the active amorphous silicon layer 4. The source/drain electrodes 7 are deposited patterned such that the source electrode and drain electrode of the n-channel transistor are not short-circuited. The metal layer 7 is besides

patterned such that the n-channel and the p-channel transistors in the circuit are connected. Consequently the layer 7 extends towards the p-channel transistor and forms the source contact therein. Now follows a layer 8 of an isolating material, for instance silicon nitride, polyimide or another dielectric in order to isolate the source/drain electrodes 7 against the active organic semiconductor layer 9 which is formed of α-hexathienylene (α-6T) and which for instance may be deposited by vacuum sublimation. Finally, the prior art circuit comprises the drain electrode 10 of the p-channel transistor.

The contact metal may be made of an evaporated or sputtered layer of Au or Ag and will be connected to the positive supply voltage. This prior art complementary transistor circuit is then in a final step coated with a

passivation layer 11. e.g. of silicon nitride or polyimide, to protect the

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deposited on a substrate and covered by a layer of silicon nitride which forms extends beyond this where it forms n' doped areas for source and drain in the the gate isolator. The inorganic active semiconductor material is here shown material of the source electrode of the inorganic transistor may be of another electrode is itself then deposited over the active semiconductor material and deposited over the gate isolator such that the source and drain electrodes of in the form of hydrogenated amorphous silicon (a-Si:H) and provided such A section through a first embodiment of a complementary transistor circuit that it registers with the gate electrode of the inorganic transistor, but also norganic transistor. The contact material proper for the drain or source hin-film structure. Over both the inorganic and the organic transistors' material for the source and drain electrodes of the organic transistor is metal than the metal in the gate electrode. Correspondingly the contact the organic transistor in each case are located on the same level in the electrodes for respectively the inorganic and the organic transistor are mutually isolated by a patterned isolation layer of silicon nitride. The according to the present invention is shown in fig. 2a. Separate gate source and drain contacts a double layer of respectively

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such that the portion between the source and drain electrodes in the organic transistor is exposed, the isolating double layer in this area in section having a re-entrant profile. The organic active semiconductor material is now provided in the form of a layer over the isolating double layer where this has not been removed and in the exposed portion thereof, such that the semiconductor material contacts both the source and the drain electrodes of the organic transistor and simultaneously also registers with the gate electrode of organic transistor. The broken re-entrant profile and the isolating double layer provide a secure electrical isolation between the organic transistor and the inorganic transistor. Of course, the active organic semiconductor material optionally may be removed where it covers the isolating double layer. In fig. 2a it is, however, retained.

polymethylmetacrylate and Novolac photoresist is provided, but patterned

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It is to be understood that the active inorganic semiconductor material is not restricted to a hydrogenated amorphous silicon, but may well consist of

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hydrogenated microcrystalline or polycrystalline silicon. The source and drain material may also be deposited separately and be different from the channel area, e.g. n⁺ doped microcrystalline hydrogenated silicon. Correspondingly the organic active semiconductor material in the organic

- fransistor is not restricted to pentacene, but may generally be made of polyconjugated organic compounds with suitable properties and be formed by several such. As example of such polyconjugated organic compounds and as known in the art, it may be mentioned conjugated oligomers, the units of which includes or consists of phenylene groups which may be substituted, ortho-fused or ortho- and peri-fused aromatic polycyclic hydrocarbons with 4 to 20 fused rings, polyenes with the formula H-C(T₁)=C(T₂)- H where T₁
- and T₂ independently represent –H or a lower alkyl and r is an integer which may vary from 8 to 50, as well as conjugated oligomers whose repeating units contain at least a five-link heterocycle. Generally shall a polyconjugated compound used as active semiconductor material in the organic semiconductor transistor contain at least 8 conjugated bonds and have a molecular weight which is not greater than about 2000. For a more comprehensive discussion of these materials it shall besides be referred to the above-mentioned US patent no. 5 347 144 (Garnier & al.).
- As an alternative to the embodiment in fig. 2a. the isolation of the active semiconductor material in the p-channel transistor may be achieved with a simplified version of the complementary thin-film transistor circuit. In fig. 2b this is shown by providing a photoresist layer over the complementary thin-film transistor circuit, whereafter the organic active semiconductor
 - of the photoresist may be retained as shown in fig. 2b, but it may also be removed such this is shown in fig. 2c. In each case the active semiconductor material in the organic transistor becomes electrically isolated against the inorganic transistor. In that connection it shall be remarked that generally it has been regarded as a problem to remove active organic semiconductor.
 - has been regarded as a problem to remove active organic semiconductor material by etching, as such materials usually are damaged or destroyed when they are subjected to common photoresists and chemicals for treatment of the photoresist. However, it has turned out that a water-based etch process with water-based material provides very good results. In the patterning of e.g. organic optoelectronic material may e.g polyvinyl alcohol as solvent and gelatine as photoresist be an advantageous alternative. Besides are both

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photolithography and printing other possible alternatives to etching – particularly printing may in the long run turn out to be both the simplest and cheapest.

Fig. 3a shows a section through an organic/inorganic thin-film transistor according to the present invention where an organic thin-film transistor with an n-channel organic semiconductor is employed. Fig. 3 shows the simplest embodiment possible, wherein separate gate electrodes are provided on the substrate, the gate isolator consists of the same material in both cases and the metal for the source/drain electrode similarly is the same for both transistors.

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10 As an example of an organic n-channel material may be mentioned copper hexadecafluorophtalocyanine (F₁₆CuPc) (see Y.Y. Lin & al., "Organic complementary ringoscillators", Appl. Phys. Lett., Vol. 74 No. 18 (1999)). This organic semiconductor shows field-effect mobilities up to 10⁻² cm/Vs and is not as sensitive to external conditions as other organic semiconductor materials of the n-type such as buckminsterfullerene (C₆₀).

Organic n-channel thin-film transistors based on copper-hexadecalluorophtalocyanine (F₁₆CuPc) or another organic semiconductor material of the n-type may be combined with one of several inorganic p-channel semiconductor materials in order to form the complementary thin-film transistor circuit.

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As examples of suitable inorganic semiconductors of the p-type may be mentioned p-channel amorphous silicon which has field effect mobilities comparable with F₁₆CuPc. or copper-doped polycrystalline germanium (pc-Ge:Cu) which in the literature is shown used in combination with indium-doped cadmium selenide (Cd-Se:In) in a complementary polycrystalline thin-film technology (see J. Doutreloigne & al., "The electrical performance of a complementary CdSe:In/Ge:Cu thin film transistor technology for flat panel displays", Solid-State Electronics, Vol. 34 No. 2 (1991)). Polycrystalline germanium has displayed field-effect mobilities of about 5-15 cm²/Vs, but requires a more complicated processing

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than amorphous silicon.

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Fig. 3b shows an embodiment of the complementary thin-film transistor circuit according to the invention with an n-channel transistor. The embodiment in fig. 3b is analog to that in fig. 2a, but with the same metal used for the source and drain electrodes in both transistors. The isolating double layer may be realized as in fig. 2a, namely consisting of polymethylmetacrylate and Novolac photoresist such that the portion above the n-channel organic semiconductor is exposed, the isolating double layer also here being broken by a re-entrant profile. The active semiconductor in the n-channel organic transistor will then be isolated from the p-channel

inorganic transistor, something which may be advantageous, but which is not a necessary condition for using an organic active n-channel semiconductor material.

The isolation of the organic active n-channel semiconductor material may also be achieved in corresponding manner as shown for the embodiment in fig. 2b, namely as shown in fig. 3c, where a photoresist is etched and masked such that the n-channel organic active semiconductor is isolated. The etch mask. i.e. the photoresist, may also here be removed from the organic n-channel transistor and it is then obtained the variant which is shown in fig. 3d of the embodiment in fig. 3c.

There shall now with reference to figs. 4a-4r which schematically show the process scheme for integrated complementary a-Si:H organic transistor technology be given a description of specific features in the fabrication of the complementary thin-film transistor circuit according to the invention. The inorganic a-Si:H thin-film transistor is made in a process which provides an inverted staggered three-layer structure, something which shall be described more closely in the following. The layers of a-Si:H/SiN were deposited using of plasma-enhanced chemical vapour deposition. The subsequent process step comprises standard lithographic methods and wet etching techniques as well as sputtered deposition of source and drain metal for the

inorganic thin-film transistor. The source and drain electrodes of the organic thin-film transistor were deposited by means of thermal evaporation. In order to isolate the active semiconductor material of the organic thin-film transistor, in this case pentacene, a re-entrant photoresist profile was used consisting of polymethylmetacrylate (PMMA) and Novolac photoresist which together forms an isolating double layer in the complementary transistor circuit. This is a necessary step, as thin-film transistors with pentacene as

p-channel active semiconductor material usually will have a positive threshold, i.e. a positive voltage must be used on the gate electrode to turn the transistor off. It is hence necessary to isolate an active p-channel semiconductor of pentacene in the organic transistor in order to prevent leakage in the pentacene layer, but as pentacene is sensitive to most forms of chemical processing, it is difficult to achieve isolation with the use of photolitography after the deposition of the organic semiconductive layer. With the method according to the invention the isolation is achieved during the deposition of the pentacene layer by breaking this over the re-entrant double-layer profile in the organic transistor. The maximum temperature which was used during the fabrication was 250°C.

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photoresist is now patterned with another mask II in order to actively define a uppermost silicon nitride layer is etched and in the subsequent process step in the lowermost nitride layer by means of a third mask III. The etching itself of shown in fig. 4b. By means of plasma-enhanced chemical vapour deposition, fig. 4f the layer of hydrogenated amorphous silicon is etched. In the process however, substantially will be self-explanatory to a person skilled in the art. In fig. 4a the gate electrode metal is deposited on the substrate by sputtering a tri-layer structure is thereafter deposited. consisting of a gate isolator SiN_x step shown in fig. 4g a photoresist is patterned for etching of i-stopper and explicitly be discussed with a concrete short reference to figs. 4a-4r which, over both gate electrodes. thereabove a layer of hydrogenated amorphous silicon and finally an isolation layer, once again formed of silicon nitride, Now the process steps for the fabrication of a transistor of this kind shall and then the separate gate electrodes are patterned with a first mask I as thin-film transistor with hydrogenated amorphous silicon. In fig. 4e the the i-stopper and the lowermost silicon nitride layer is shown in fig. 4h. such as shown in fig. 4c. In the subsequent step shown in fig. 4d a

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In order to realize the source and drain areas of the n-channel transistor as shown in fig. 4i n⁺ a-Si:H is now deposited by means of plasma-enhanced chemical vapour deposition and in the subsequent process step in fig. 4j this takes place by means of a fourth mask IV for patterning a photoresist for lift-off of source/drain electrode metal. This is sputtered in the process step as shown in fig. 4k and is denoted with M2 which may be a metal different from the first metal used in the gate electrodes. In the process step shown in fig. 4l the source/drain metal M2 for the organic transistor was lifted off and

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then follows in the process step shown in fig. 4m an etching of the n* layer of hydrogenated amorphous silicon which hence shall provide the source and drain areas of the inorganic transistor.

Now follows in the process step shown in fig. 4n a patterning of a photoresist for lift-off of the metallization of the organic thin-film transistor. This takes place by means of a fifth mask V. A metal layer of a third metal M3 is now deposited over the whole transistor circuit, as shown in fig. 4o, and then follows the lift-off of this metal layer M3, such that the organic thin-film transistor appears with source and drain electrodes of the metal M3 provided in the same level in the thin-film structure. In order to isolate the organic thin-film transistor electrically against the inorganic thin-film transistor is now by means of photo-lithography deposited a double layer consisting of polymethylmetacrylate PMMA and for instance Novolac photoresist. The

in the same level in the thin-film structure. In order to isolate the organic thin-film transistor electrically against the inorganic thin-film transistor is now by means of photo-lithography deposited a double layer consisting of polymethylmetacrylate PMMA and for instance Novolac photoresist. The isolating double layer is patterned such that the source and drain electrodes of the metal M3 for the organic thin-film transistor are exposed between re-entrant broken profiles of the isolating double layer, such this is shown in fig. 4q. Finally is now the organic active semiconductor material deposited in the form of pentacene over the whole circuit and provides in the exposed portion the active p-channel semiconductor material of the organic transistor.

It shall be understood that the pentacene layer where it covers the isolating double layer besides may be removed therefrom in a concluding not shown process step. Further may, of course, electrically isolating passivation and planarization layers be deposited over the whole complementary thin-film circuit, such this is known in the art, but not here specifically shown. The complementary organic thin-film transistor circuit according to the invention now appears substantially as shown in fig. 4r and corresponding to the embodiment shown in fig. 2a.

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The tri-layer etch process as used with the present invention and as rendered in the process steps as shown in figs. 4c-h shall now be discussed in somewhat greater detail with reference to figs, 5a-5d. In the tri-layer etch process as shown in fig. 5a, a triple layer of silicon nitride, undoped hydrogenated amorphous silicon and a further layer of silicon nitride are deposited on the patterned gate electrode. The uppermost silicon nitride layer is patterned as shown in fig. 5b and an n⁺ doped layer of amorphous hydrogenated silicon is deposited all over as shown in fig. 5c. The metal of

is patterned as shown in fig. 5b and an n' doped layer of amorphous

35 hydrogenated silicon is deposited all over as shown in fig. 5c. The metal of
the source and drain electrodes is patterned and the doped amorphous silicon

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fig. 5d. As the uppermost silicon nitride layer protects the channel area in the the source and drain electrodes must be patterned on the top of the uppermost silicon nitride layer which is patterned with the channel length, this requires tri-layer process requires two deposition steps of amorphous silicon and as naterial over the uppermost silicon nitride layer etched away, as shown in inorganic thin-film transistor, this etch step is not critical. However, the a more aggressive photolithography for a given channel length.

in the channel area is a critical step. Typically back-channel etching results in hydrogenated amorphous silicon in the channel area is etched away, such this is shown in fig. 6b and fig. 6c respectively. The back-channel etch process is very simple, but the etching of the n doped hydrogenated amorphous silicon inorganic thin-film transistors with poorer quality than that may be obtained followed by undoped hydrogenated silicon and nt doped silicon as well as a further layer of n doped hydrogenated amorphous silicon. This is shown in The back-channel etch process is shown in fig. 6a-6c. An isolation layer of silicon nitride is deposited over the gate electrode and the substrate, and fig. 6a. The source and drain electrodes are patterned and the doped by using a three-layer etch process.

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invention. Functionally the inverter in fig. 7a corresponds substantially to the electrode contact may then be deposited in the same process step as shown in ransistor as well as the inverter gate contact against the inorganic transistor. inverter is based on a p-channel semiconductor material, viz. pentacene, and semiconductor material in the inorganic transistor. As the input signal to the complementary transistor circuit according to prior art as rendered in fig. 1, out is based on the embodiment according to the present invention such this fig. 4a-4b with the use of mask I. As in fig. 2a the isolating double layer of polymethylmetacrylate on Novolac photoresist will isolate both the organic hydrogenated amorphous silicon in doped and undoped form is used as the inverter shall be conveyed to the gate electrodes, there is for this purpose for instance is shown in fig. 2a. As therein the organic transistor of the nverter, be removed. The well-known schematic circuit diagram of the Fig. 7a shows a schematic section through an inverter formed with the provided a gate electrode contact as shown to left in fig. 7a. This gate isolating double layer as well as over the gate electrode contact of the integrated complementary thin-film transistor circuit according to the Besides may also here the pentacene layer which is provided over the 33 8 25 33

shown by the line drawing in fig. 7c. The organic thin-film transistor is here complementary transistor circuit and a method according to the invention is ocated at left and the inorganic thin-film transistor in the complementary inverter shown in fig. 7b and an inverter realized with use of a

Fig. 8a shows the voltage transfer curves for different supply voltages for an inverter with a β ratio of 1. The β ratio is here defined by

thin-film transistor circuit at right in fig. 7c.

S

$$\beta = \frac{(W/L)_{a-N:H}}{W/L_{pertacenc}}$$

In this regard it shall be remarked that in CMOS circuits both transistors may the voltage levels of the complementary thin-film transistor circuit according to the invention. The transition current for the inverter reaches a top near the supply voltage of 20 V. The on voltage of the inverter is equal to the supply logic transition voltage and is otherwise very low, such this is evident from voltage and the off voltage is 0 V. This shows the complete maintenance of - The inverter shows sharp transitions with a gain which exceeds 22 for a sometimes defined as the width/length relationship W/L for the n-channel levice divided by the length/width relationship for the p-channel device. be operated both as driver and load. Due to a topological similarity β is ig. 8b. This shows that the complementary thin-film transistor circuit 2 15

according to the present invention has a true complementary behaviour.

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gate is of course obtained, the output of which then becoming the inverted of gate realized by means of a complementary transistor circuit according to the corresponding schematic circuit diagram in fig. 9b. By connecting the output With the complementary thin-film transistor circuit according to the present known in the CMOS-technology. An example of a complementary NANDnvention it is, of course, possible to realize logic gates as otherwise wellof the NAND gate to the inverter shown in fig. 7c a complementary AND the output signal from the NAND gate. The voltage transfer curve for present invention is shown in the line drawing in fig. 9a and the 25

corresponding Boolean functions be realized with the use of a NAND gate as that generally may all logic gates as known in the CMOS technology and the hese are shown in fig. 8a. A person skilled in the art will, of course, realize different input voltages for the NAND gate is shown in fig. 9c and has the same properties as the voltage transfer curves for the simple inverter such 2

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shown in fig. 9a and inverters as shown in fig. 7c. The integrated complementary thin-film transistor circuit according to the invention is generally used for realizing logic gates in complementary thin-film technology.

5 By means of the integrated complementary thin-film circuits ring oscillators were made with respectively 5 and 11 inverter stages and with different β ratios. These ring oscillators show a single gate delay as low as 5 μs, a gate power dissipation less than 0.2 μW per stage and a power delay product as low as 15 pJ. The gate delay decreases fast with the increasing supply voltage, such that high operating frequencies may be obtained with the relatively low supply voltage.

A line drawing of a five-stage ring oscillator is shown in fig. 10 and with the circuit diagram rendered in fig. 11. In addition to the five inverter stages an additional sixth inverter is used for isolating the circuit from the capacity load of an oscilloscope used for measuring the characteristics of the ring oscillator. From the measured oscillation frequency the delay of a single inverter stage can be derived. Fig. 12a shows the single gate delay for the shown five-stage ring oscillator, fig. 12b power dissipation and fig. 12c the power delay product for the same, all figures showing these characteristics for a β ratio of 1/2.

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A ring oscillator with eleven inverter steps is realized in corresponding manner with the use of the integrated complementary thin-film circuit according to the present invention, but not shown herein. Fig.13a, 13b and 13c, however, show the corresponding characteristics for this eleven-stage ring oscillator as shown in fig. 12a-12c, but with a β ratio of 1/3.

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The methods according to the present invention are simple and hence make it possible to fabricate integrated complementary thin-film transistor circuits according to the invention at low costs. Complementary transistor circuits have an inherent low static power consumption, something which is of importance for applications based on battery power. This makes the complementary thin-film transistor circuit according to the invention applicable in control circuits for liquid crystal displays in portable PCs, so-called "lap-tops" or for low-level implementation such as programmable tags. The circuits according to the invention have high switching amplification and very good maintenance of the logic level in addition to low

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static power consumption. The gate delay in the transistor circuits fabricated according to the invention measured by means of ring oscillators is as mentioned as low as 5µs, the fastest speed up to now obtained with circuits which use organic transistors.

- The hybrid integrated complementary thin-film technology, wherein the organic thin-film transistor may be an n-channel transistor and the organic transistor a p-channel transistor or vice versa, is of course, not restricted to use of the active semiconductor materials as mentioned in the exemplary embodiments. The on-going development of suitable organic as well as
- inorganic semiconductor materials makes it probable that in the future both n- as well as p-channel active organic semiconductor materials and correspondingly n- as well as p-channel inorganic active semiconductor materials with further improved properties may be employed. Composite inorganic semiconductor compounds may be of interest and the same applies to single crystal silicon, while on the other hand gallium arsenide for the time being appears less probable. but shall in no way be excluded in future hybrid complementary thin-film transistor circuits of the kind disclosed herein.

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CLAIMS

An integrated inorganic/organic complementary thin-film transistor circuit comprising a first and a second transistor which are operatively connected and provided on a common substrate, wherein the first transistor is an inorganic thin-film transistor and the second transistor an organic thin-film transistor, and wherein the complementary thin-film transistor circuit forms a multilayer thin-film structure, characterized in that the inorganic thin-film transistor is an n-channel transistor and that the organic thin-film transistor is a p-channel transistor, or vice versa, the organic active transistor material in each case being respectively a p-channel organic semiconductor material or an n-channel organic semiconductor

that separate gate electrodes are provided for each of the transistors, that the organic active semiconductor in an organic p-channel transistor in each case is provided electrically isolated from the inorganic n-channel transistor, and that the organic active semiconductor in an organic n-channel transistor optionally is provided electrically isolated from the inorganic p-channel

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- A complementary thin-film transistor circuit according to claim 1, characterized in that the inorganic active semiconductor material is selected among hydrogenated amorphous silicon (a-Si:H), hydrogenated or unhydrogenated microcrystalline silicon (μc-Si:H;μc-Si), hydrogenated or unhydrogenated polycrystalline silicon (pc-Si:H;μc-Si), single crystal silicon, copper-doped polycrystalline germanium (pc-Ge:Cu), cadmium selenide (CdSe), cadmium telluride (CdTe), or composite inorganic semiconductors based on said materials, possibly in single crystal form.
- A complementary thin-film transistor circuit according to claim 2 wherein the inorganic transistor is an n-channel transistor,
 characterized in that the inorganic active semiconductor material is hydrogenated amorphous silicon (a-Si:H).
- A complementary thin-film transistor circuit according to claim 2, wherein the inorganic transistor is a p-channel transistor, characterized in that the inorganic active semiconductor material is a

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p-channel silicon material, particularly p-channel hydrogenated amorphous silicon (a-Si:H).

- A complementary thin-film transistor circuit according to claim 1, characterized in that the active semiconductor material in the organic
- 5 thin-film transistor comprises at least one polyconjugated organic compound with a specific molecular weight.
- A complementary thin-film transistor circuit according to claim 5, characterized in that the polyconjugated organic compound or compounds are selected among conjugated oligomers, polycyclic aromatic hydrocarbons,
 - 10 particularly polyacenes, or polyenes.
- A complementary thin-film transistor circuit according to claim 6, wherein the organic thin-film transistor is a p-channel transistor, characterized in that the organic semiconductor material is pentacene.
- 8. A complementary thin-film transistor circuit according to claim 1,
 15 wherein the organic thin-film transistor is an n-channel transistor,
 characterized in that the organic active semiconductor material is copper
 hexadecafluorophtalocyanide (F₁₆CuPc).
- A complementary thin-film transistor circuit according to claim 1, characterized in that the source electrode and the drain electrode of the organic thin-film transistor are provided in one and the same level in the thin-film structure of the organic thin-film transistor.
- A method for fabricating an integrated inorganic/organic complementary thin-film transistor circuit comprising a first and a second transistor which are operatively connected and provided on a common substrate, wherein the first transistor is an inorganic thin-film transistor and the second transistor a organic thin-film transistor, and wherein the complementary thin-film transistor circuit forms a multilayer thin-film structure with successively deposited and patterned thin-film layers, characterized by forming the inorganic thin-film transistor as an n-channel
- transistor and the organic thin-film transistor as a p-channel transistor by depositing respectively an n-channel inorganic active semiconductor material and a p-channel organic active semiconductor material or correspondingly forming the organic thin-film transistor as an n-channel transistor and the inorganic thin-film transistor as a p-channel transistor by depositing

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first transistor is an inorganic thin-film transistor and the second transistor an circuit forms a multilayer thin-film structure with successively deposited and are operatively connected and provided on a common substrate, wherein the organic thin-film transistor, wherein the complementary thin-film transistor comprising steps for depositing separate gate electrodes of a first metal for thin-film transistor circuit comprising a first and a second transistor which patterned thin-film layers, and wherein the method is characterized by 11. A method for fabricating an inorganic/organic complementary each of the two transistors on a common substrate,

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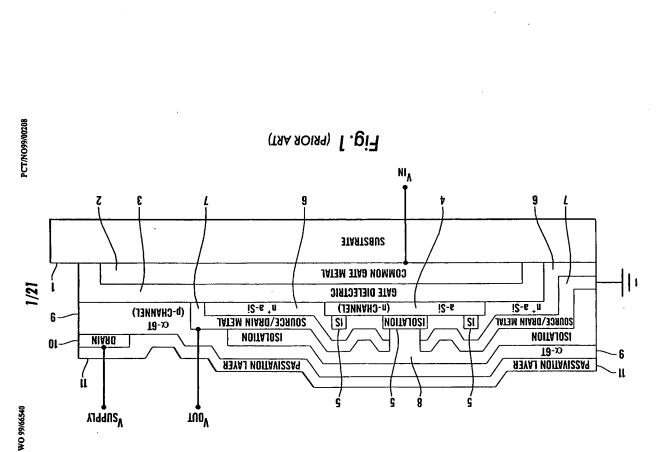
- depositing an inorganic active semiconductor in the form of hydrogenated depositing separate inorganic isolators of silicon nitride (SiNx) over each gate electrode, 2
- forms the gate electrode of the first transistor, depositing and patterning an polycrystalline silicon (n*pc-Si:H) as source and drain contacts for the first irst transistor in form of a second metal over the source and drain contacts ransistor, depositing and patterning the source and drain electrodes of the thereof, depositing and patterning the source and drain electrodes for the amorphous silicon (a-Si:H) above one of the gate electrodes which thus n* doped layer of either hydrogenated amorphous silicon (n*a-Si:H) or nydrogenated microcrystalline silicon (n*µc-Si:H) or hydrogenated 25 30
 - hin-film structure, forming an isolating double layer over the whole organic whereafter a layer of pentacene is deposited above the isolating double layer and the exposed portion of the second transistor, the pentacene layer in the second transistor in the form of a third metal in the same layer level in the exposed portion forming the active semiconductor material of the organic electrodes and the gate isolator in the second transistor become exposed, thin-film transistor and patterning this such that the source and drain 35

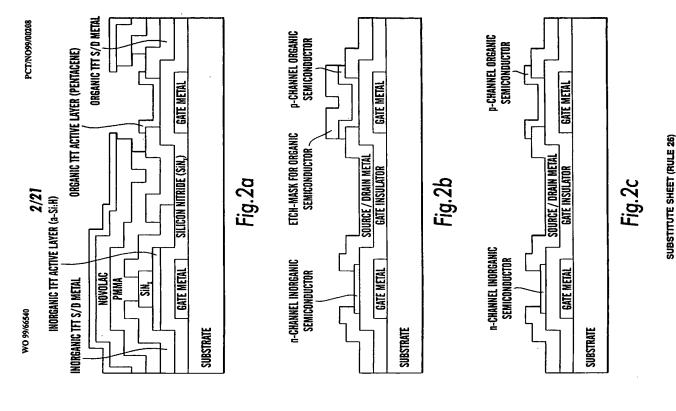
- additional pentacene layer broken by a re-entrant edge of the profile of the thin-film transistor and being provided electrically isolated against the isolating double layer.
- 12. A method according to claim 11, characterized by realizing the steps for forming the inorganic thin-film transistor in a tri-layer process which forms an inverted staggered tri-layer structure.
- 13. A method according to claim 11, characterized by realizing the steps forming the inorganic thin-film transistor in a back-channel etch process.
- semiconductor in the form of pentacene in the organic thin-film transistor by 14. A method according to claim 11, characterized by isolating the active a re-entrant profile of a broken double layer of polymethylmetacrylate (PMMA) and Novolac photoresist. 2
- hermally for forming the source and drain electrodes of the organic thin-film 15. A method according to claim 11, characterized by evaporating gold transistor

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 A method according to claim 11. characterized by optionally removing the pentacene layer which has been deposited over the isolating double layer.

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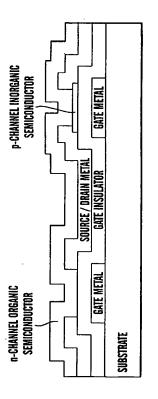


Fig.3a

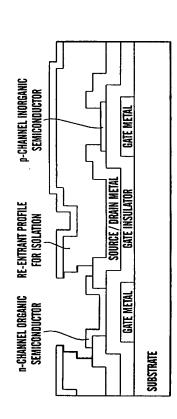


Fig.3b



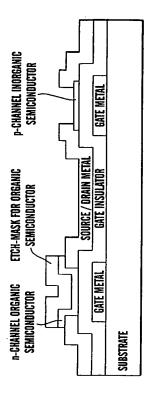


Fig.3c

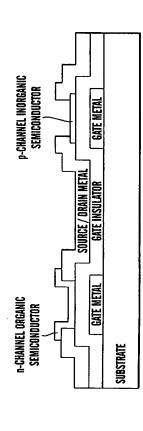


Fig.3d

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SPUTTER OF GATE METAL:

GATE METAL
SUBSTRATE

Fig.4a

DEFINITION OF GATE METAL PATTERN (MASK I).

GATE METAL GATE METAL SUBSTRATE

Fig.4b

PECVO OF TRI-LAYER:

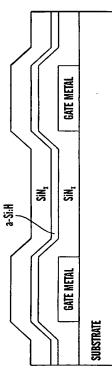


Fig.4c

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PATTERING OF PHOTORESIST FOR ACTIVE DEFINITION OF a-Si.H TFTs (MASK II);

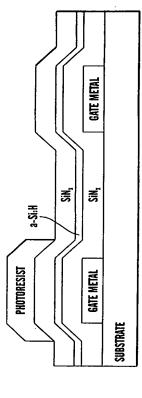


Fig.4d

ETCHING OF TOP NITRIDE LAYER:

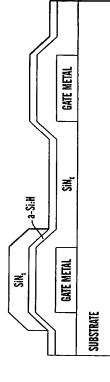


Fig.4e

ETCHING OF a-Si:H LAYER:

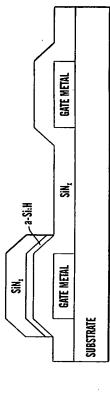


Fig.4f

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PATTERNING OF PR FOR ETCH OF 1-STOPPER AND BOTTOM NITRIDE LAYER (MASK 111);

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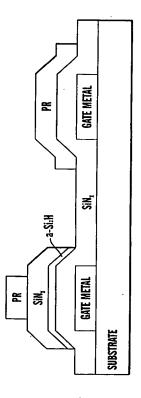


Fig.4g

ETCHING OF 1-STOPPER AND BOTTOM NITRIDE LAYER.

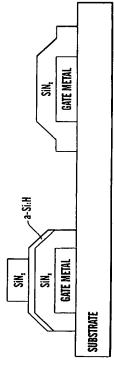


Fig.4h

PECVO OF n⁺ a-Si_:H;

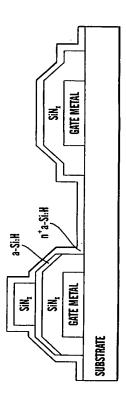


Fig.4i

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PATTERNING OF PR FOR LIFTOFF (MASK IV).

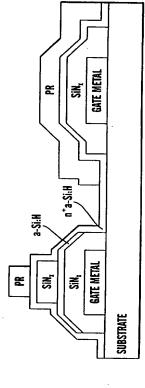


Fig.4j

SPUTTERING OF SOURCE / DRAIN METAL OF a-Si.H TFTs:

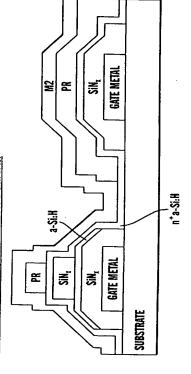
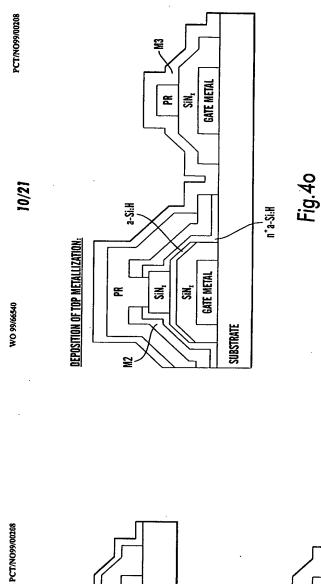


Fig.4k

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GATE METAL

GATE METAL

SUBSTRATE

Si.

n^a-Si:H

a-Si:H

X.S.

Z Z

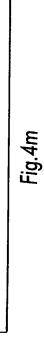
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LIFTOFF OF a-Si:H SOURCE / DRAIN METAL:

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Fig.41

ETCHING OF n*LAYER:



GATE METAL

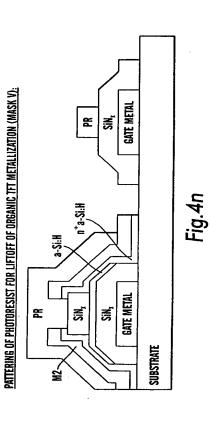
GATE METAL

SUBSTRATE

SiN

N.S.

S.



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Fig.4p

GATE METAL

GATE METAL

SUBSTRATE

S. Ž

N.S.

n⁺a-Si.H

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a-Si:H

LIFTOFF OF TOP METALLIZATION:

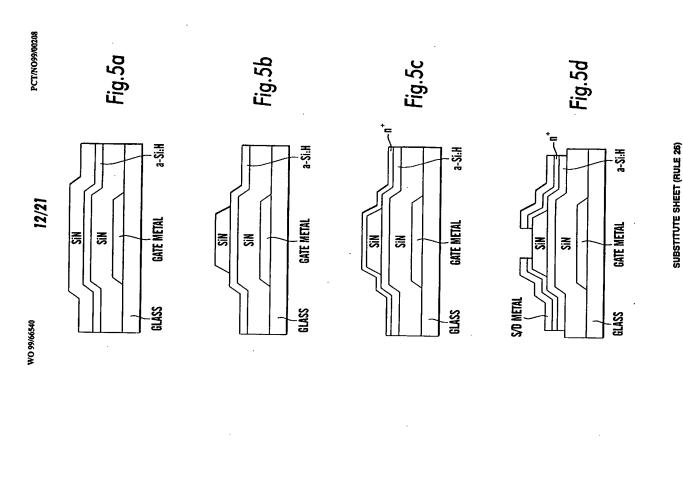


Fig.4q

n⁺a-Si.H

PENTACENE

a-Si:H

DEPOSITION OF PENTACENE ORGANIC SEMICONDUCTOR:

SiN, Gate Metal

GATE METAL

SUBSTRATE

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DOUBLE LAYER LITHOGRAPHY FOR ISOLATION:

SiN_t GATE METAL

GATE METAL

SUBSTRATE

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E E

a-Si:H

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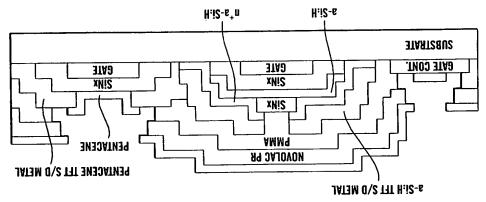
Fig.4r

n⁺a-Si:H

GATE METAL

Sis

⊾.Bi∃

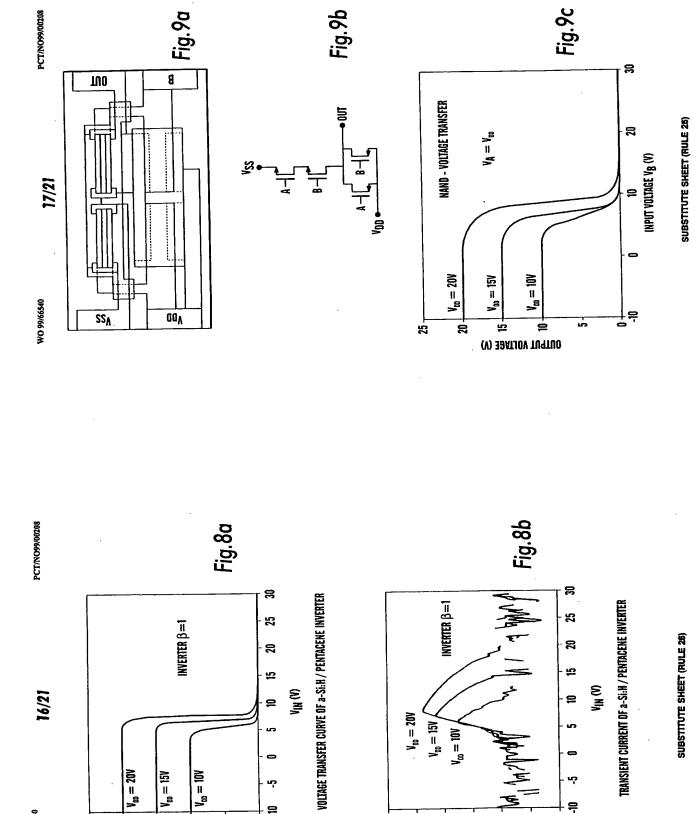


GATE METAL

S

GATE METAL

SS



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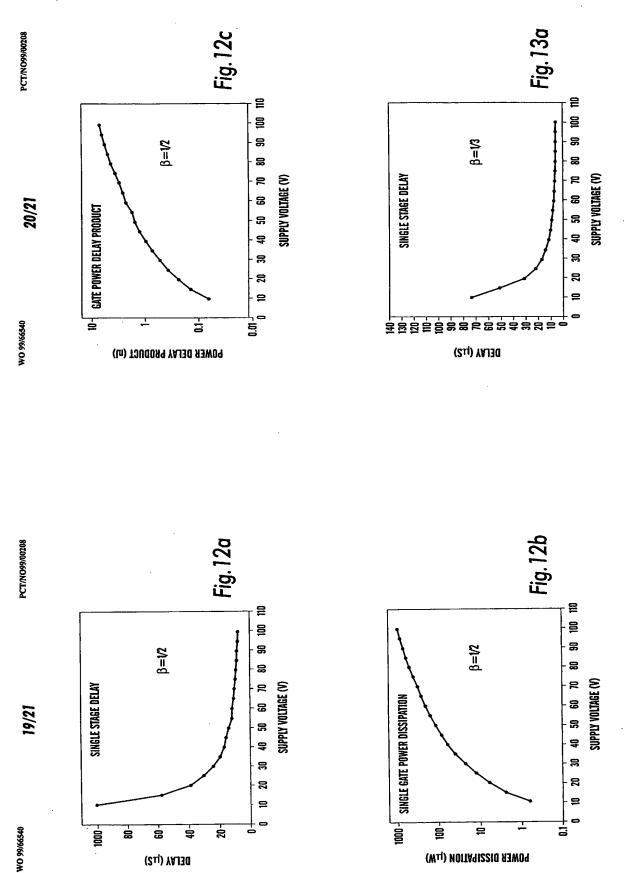
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(A) agl

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(V) TUOV



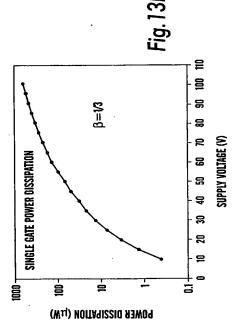
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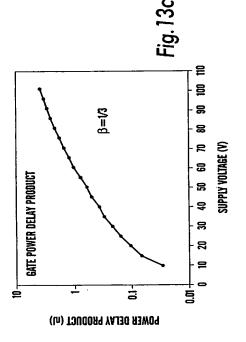
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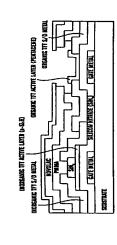
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(71) Applicant (for all designated States except US); OPTICOM ASA [NONO]; P.O. Box 1872 VHz., N-0124 Osto (NO).	TCOM (NO).	FR, GB, GR, IE, IT, LU, MC, NI, PT, SB, OAPI parent (BF, BJ, CF, CG, CJ, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).
(73) Inventors; and (75) Inventors; and (75) Inventors Applicants (for US only); JACKSON, Thomas (105.US); 1348 Decrited Drive, Stare College, PA 16801 (US), BONSE, Manhas (DRUS); Apartment 125, 201 Value (US), Sate College, PA 16803 (US), THOMASSON, Daniel, B. (US/US); 240 Los Alamos Road, Stars Roas, CA 95409 (US), HAOBN, Klant (DBUS); Apartment B. 1670 West College, Neuron, Stare College, PA 16801 (US), GUINDLACH, David, J. (US/US); Apartment PA, Warpelant Drive, Stare College, PA 16801 (US).		Published With International search report. Before the exporation of the time limit for amending the claims and to be republished in the event of the receipt of amendment. In English translation (filed in Norwegian). (88) Date of publication of the international search report.
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(\$4) TIME: AN INTEGRATED INORGANIC/ORDANIC COMPLEMENTARY THIN-FILM TRANSISTOR CIRCUIT AND A METHOD FOR ITS PRODUCTION

(57) Abstract

An integrated organic/inorganic complementary thin-film transistor circuit comprises a first and a second transistor which are operatively connected on a common substrate, wherein the first transistor is an external to the result of the inorganic thin-film transistor is an external transistor and the organic thin-film transistor is a p-channel transistor and the organic artive semiconductor material is in the case of a p-channel vice versa. Each of the transistors has a separate gate electrode and the organic artive semiconductor material is in the case of a p-channel as transistor circuit of this kind separate gate electrodes are deposited for each transistor of common substrate, the material for the source and the drain electrode of the organic thin-film transistor are deposited for the same layer level in the thin-film structure of the organic thin-film transistor are deposited on the same layer level in the thin-film structure of the organic thin-film transistor and the organic extinct that the organic extended the organic extinct organic extended to the organic active semiconductor material in an organic h-channel transistor optionally isolated from the inorganic p-channel transistor optionally isolated from the inorganic p-channel transistor optionally

1 INTERNATIONAL SEARCH REPORT

International application No. PCT/NO 99/00208

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×	US 5612228 A (CHAN-LONG SHIEH ET AL), 18 March 1997 (18.03.97), see the	whole document	1-4,9-10
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Publication date 11/05/95 21/04/93 10/01/92 23/01/92 17/07/92 23/07/97 31/07/97 05/09/97 69104204 D,T 0537240 A,B 2664430 A,B 9201313 A 2671542 A 0785578 A 9199732 A 9232589 A Patent family member(s) NO. 3 유마氏공氏 윤육 18/03/97 30/07/97 13/09/94 29/04/97 Publication date EP 0786820 A2 US 5347144 A US 5612228 A 5625199 A Patent decument cited in search report S

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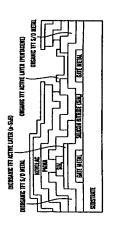


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(71) Applicant (for all designated States except US); OPTICOM ASA [NONO]; P.O. Box 1872 VIRs. N-0124 Oalo (NO).	PTICO).	
(72) Inventorry and (75) Inventorry and (75) Inventorry and (75) Inventorry and (75) Inventorry (75) Inventorr	Thomas A 1680, 201 Vain (ASSON) the Ross Operation (A 1680) at F1, 44,	Published With international search report. With international search report. With international search report. With international of the time limit for amending the claims and to be republished in the even of the receipt of amendment. In English prostation (filed in Norwegian). (88) Date of publication of the international search report:

(\$4) TIME: AN INTEGRATED INORGANICORGANIC COMPLEMENTARY THIN-FILM TRANSISTOR CIRCUIT AND A METHOD FOR ITS PRODUCTION

(74) Agent: LEISTAD, Geirr, 1.; Opticom ASA, P.O. Box 1872 Viles, N-0124 Oslo (NO).



(57) Abstract

An integrated organic/inorganic complementary thin-film transistor circuit comprises a first and a second transistor which are operatively connected on a common substante, wherein the first transistor is an inchange of thin-film transistor and the second an organic thin-film transistor. The inorganic thin-film transistor is an inchange that the film transistor is an inchange that the film transistor is an inchange that the common substance is an inchange of the film film transistor in a sparate game felecthed and the organic active semiconductor material is in the case of a p-channel transistor or an international transistor. In a first method for fibricating at transistor circuit of this kind separate game electrodes are deposited for each transistor on a common substance, the material for the source find the transistor circuit of this kind separate game electrodes are deposited on the same layer level in the thin-film structure of the organic thin-film transistors are deposited for each transistor on a common substance, the material for the source from the inorganic n-channel transistor, and the organic carrier semiconductor material in an organic n-channel transistor optionally stolated from the inorganic p-channel transistor.

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AN INTEGRATED INORGANIC/ORGANIC COMPLEMENTARY THIN-FILM TRANSISTOR CIRCUIT AND A METHOD FOR ITS PRODUCTION

The invention concerns an integrated inorganic/organic complementary thin-film transistor circuit, comprising a first and a second transistor which is operatively connected and provided on a common substrate, wherein the first transistor is an inorganic thin-film transistor and the second transistor an organic thin-film transistor and wherein the complementary thin-film transistor circuit forms a multilayer structure.

The present invention also concerns methods for fabricating an integrated inorganic/organic complementary thin-film transistor circuit, comprising a first and a second transistor which are operatively connected and provided on a common substrate, wherein the first transistor is an inorganic thin-film transistor and the second transistor an organic thin-film transistor, and wherein the complementary thin-film transistor circuit forms a multilayer thin-film structure with successively deposited and patterned thin-film layers.

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Integrated circuits of silicon realized as complementary metal-oxide semiconductors dominate the markets for a number of microelectronic applications such as microprocessors. But complementary circuits may also be of interest for more general application, e.g. in portable battery-operated electronic products, as they can provide very low static power dissipation for digital circuits. It has, however, turned out to be difficult to realize complementary integrated thin-film circuits with sufficient performance for commercial applications.

Hydrogenated thin-film transistors of silicon (a-Si:H TFT) have found a new application in thin-film components, particularly in liquid crystal displays with active matrix. However, complementary a-Si:H circuits are problematic, as the hole transport mobility typically is much lower than the electron transport mobility. Recently TFTs with organic active layers have been fabricated and with performance comparable to that which can be obtained with amorphous silicon devices (a-Si:H devices).

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thin-film field-effect transistor with an MIS structure which includes a thin semiconductor layer between the source and drain electrode. The thin semiconductor layer between a surface of a thin-film made of isolating material which at its second surface contacts a conducting grid. The

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semiconductor is made of at least one polyconjugated organic compound with a determined molecular weight. As organic semiconductor material Garnier & al. among others mention different various aromatic polycyclic hydrocarbons and among these polyacenes. The transistor of Garnier & al. is stated to be particularly suited as a switching or amplifying device.

Also simple organic complementary thin-film transistor circuits have been discussed in the literature, but have not shown the desired performance properties. Further attempts have been made building complementary circuits with combinations of inorganic and organic devices on separate substrates and with external connection.

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In US patent no. 5 625 199 (Baumbach & al.) there is, however, disclosed a complementary circuit with an inorganic n-channel thin-film transistor and an organic p-channel thin-film transistor employs hydrogenated amorphous silicon as active material and the p-channel of the organic thin-film transistor employs α-hexathienylene (α-6T) as active semiconductor material. The complementary thin-film transistor circuit according to Baumbach & al. can be used for implementing an integrated complementary inverter or other complementary circuits.

The integrated complementary inorganic/organic thin-film transistor according to Baumbach & al. is, however, encumbered with a number of disadvantages both from a processual point of view as well as with regard to general application in more comprehensive transistor circuits. Thus Baumbach & al. propose to provide respectively the source and drain electrodes on both sides of the organic semiconductor layer, something which firstly is not necessary and additionally comports a number of disadvantages in the fabrication. Further the source and drain contacts of the organic thin-film transistor must be formed in different steps and it will also be difficult to pattern contacts on the top of the organic semiconductor unless shadow masks are used.

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30 Nor has the complementary thin-film transistor according to Baumbach an isolated organic semiconductor material in the organic thin film transistor.

As it will be desirable to be able to turn the inorganic transistor on and to turn the organic transistor off or vice versa using potential with the same sign, this may be problematic. In the complementary thin-film transistor according to Baumbach & al. it is probable that an undesirable large leakage

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of organic materials which may be used for forming active semiconductors of materials proposed. It is, however, evident from Baumbach & al. that the use n-channel and the p-channel transistor. More complex transistor circuits built will be problematic if the complementary thin-film transistor shall be used in complex circuits. An inverter realized according to Baumbach & al. switches Another disadvantage of the complementary thin-film transistor according to the n-type demands relatively complicated and costly fabricating processes from complementary devices shall require that common electrodes are not used in these. Even in simple inverters a common gate electrode will give complementary thin-film transistor according to Baumbach & al. uses the inorganic transistor as n-channel transistor and the organic transistor as as stated in the cited US patent at about 5V at a supply voltage of 7,2 V. p-channel transistor. something which is understandable in light of the Baumbach & al. is that a common gate electrode is used both for the increased stray capacitance. Further it shall be remarked that the and hence is not easy to realize for the time being.

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A first object of the present invention is hence to overcome the disadvantages which are connected with prior art and particularly to provide an integrated complementary inorganic vorganic thin-film transistor circuit which is suited for use in large transistor circuits. Another object is to provide complementary thin-film transistor circuits which allow a cheap fabrication and simultaneously have low static power consumption, such that they can be used in portable battery-operated equipment.

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A further object of the present invention is to provide an uncomplicated and inexpensive method for fabricating integrated complementary inorganic/organic thin-film transistor circuits and this in as few process steps as possible, while a device with good electric properties is obtained and whereby it particularly shall be possible to realize the inorganic transistor as an n-channel transistor and the organic transistor or

The above-mentioned and other objects are achieved with an integrated inorganic/organic complementary thin-film transistor circuit which according to the invention is characterized in that the organic thin-film transistor is an n-channel transistor and that the organic thin-film transistor is a p-channel transistor, or vice versa, the organic active transistor material in each case

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being respectively a p-channel organic semiconductor material or an n-channel organic semiconductor material, that separate gate electrodes are provided for each of the transistors, that the organic active semiconductor in an organic p-channel transistor in each case is provided electrically isolated from the inorganic n-channel transistor, and that the organic active semiconductor in an organic n-channel transistor optionally is provided electrically isolated from the inorganic p-channel transistor.

According to the invention the inorganic active semiconductor material is advantageously selected among hydrogenated amorphous silicon (a-Si:H), hydrogenated or unhydrogenated microcrystalline silicon (µc-Si:H;µc-Si), hydrogenated or unhydrogenated polycrystalline silicon (pc-Si:H;pc-Si), single crystal silicon. copper-doped polycrystalline germanium (pc-Ge:Cu), cadmium selenide (CdSe), cadmium telluride (CdTe), or composite inorganic semiconductors based on said materials.

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Where the inorganic thin-film transistor is an n-channel transistor, the inorganic active semiconductor material is preferably amorphous silicon (a-Si:H), and where the inorganic transistor is a p-channel transistor, the inorganic active semiconductor material is preferably a p-channel silicon material, particularly p-channel hydrogenated amorphous silicon (a-Si:H).

In an advantageous embodiment the active semiconductor material in the inorganic thin-film transistor comprises at least one polyconjugated organic compound with a specific molecular weight. It is then advantageous that the polyconjugated organic compound or compounds are selected selected among conjugated oligomers, polycyclic aromatic hydrocarbons, particularly

25 polyacenes. or polyenes.

Where the organic thin-film transistor is a p-channel transistor, it is advantageous that the organic active semiconductor material is pentacene, and where the organic thin-film transistor is an n-channel transistor, it is advantageous that the organic active semiconductor material is copper

30 hexadecafluorophtalocyanide.

Finally, it is according to the invention particularly advantageous that the source electrode and the drain electrode of the organic thin-film transistor is provided in one and the same level in the thin-film structure of the organic thin-film transistor.

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isolated from the inorganic n-channel transistor and optionally providing the organic thin-film transistor on the same level in the thin-film structure of the p-channel organic active semiconductor material or correspondingly forming A first method for fabricating an integrated inorganic/organic complementary n-channel organic active semiconductor material and a p-channel inorganic the organic thin-film transistor as an n-channel transistor and the inorganic forming the inorganic thin-film transistor as an n-channel transistor and the thin-film transistor as a p-channel transistor by depositing respectively an organic active semiconductive material in an organic n-channel transistor depositing material for the source electrode and the drain electrode of the organic thin-film transistor and in each case providing the organic active respectively an n-channel inorganic active semiconductor material and a thin film transistor circuit is according to the invention characterized by semiconductor material in an organic p-channel transistor electrically active semiconductor material, depositing separate gate electrodes for respectively the first and the second transistor on a common substrate, organic thin-film transistor as a p-channel transistor by depositing electrically isolated from the inorganic p-channel transistor. 2

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electrodes of the first transistor in form of a second metal over the source and the whole organic thin-film transistor and patterning this such that the source hydrogenated polycrystalline silicon (n*pc-Si:H) as source and drain contacts characterized by comprising steps for depositing separate gate electrodes of a layer level in the thin-film structure, forming an isolating double layer over electrodes for the second transistor in the form of a third metal in the same gate electrode, depositing an inorganic active semiconductor in the form of and drain electrodes and the gate isolator in the second transistor become exposed, whereafter a layer of pentacene is deposited above the isolating hydrogenated amorphous silicon (a-Si:H) above one of the gate electrodes which thus forms the gate electrode of the first transistor, depositing and depositing separate inorganic isolators of silicon nitride (SiN $_{\!\scriptscriptstyle X})$ over each complementary thin-film transistor circuit is according to the invention patterning an \boldsymbol{n}^{\star} doped layer of either hydrogenated amorphous silicon drain contacts thereof, depositing and patterning the source and drain for the first transistor, depositing and patterning the source and drain $(\pi^{+}a\text{-}Si:H)$ or hydrogenated microcrystalline silicon ($\pi^{+}\mu c\text{-}Si:H)$ or first metal for each of the two transistors on a common substrate, A second method for fabricating an integrated inorganic/organic 35 8

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layer in the exposed portion forming the active semiconductor material of the double layer and the exposed portion of the second transistor, the pentacene the additional pentacene layer broken by a re-entrant edge of the profile of organic thin-film transistor and being provided electrically isolated against

the isolating double layer.

realized in a tri-layer process which forms an inverted staggered three-layer In an advantageous embodiment of the last-mentioned method according to the invention the steps for forming the inorganic thin-film transistor are structure.

In another advantageous embodiment of the last-mentioned method according to the invention the steps for forming the inorganic thin-film transistor are realized in a back-channel etch process. 2

In an advantageous embodiment of the last-mentioned method according to double layer of polymethylmetacrylate (PMMA) and Novolac photoresist. organic thin-film transistor is isolated by a re-entrant profile of a broken the invention the active semiconductor in the form of pentacene in the

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In an advantageous embodiment of the last-mentioned method according to the invention gold is evaporated thermally for forming the source and drain electrodes of the organic thin-film transistor.

Finally, the pentacene layer which is deposited over the isolating double layer can optionally be removed. 2

exemplary embodiments and with reference to the accompanying drawings The invention shall now be explained in more detail in connection with

fig. I shows a complementary thin-film transistor circuit according to prior art as exemplified by the above-mentioned US patent No. 5 675 199,

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fig. 2a a first embodiment of the complementary thin-film transistor circuit according to the invention,

fig. 2b a second embodiment of a complementary thin-film transistor circuit according to the invention,

fig. 2c a variant of the embodiment in fig. 2b,

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fig. 3a a third embodiment of the complementary thin-film transistor circuit according to the invention.

fig. 3b a fourth embodiment of the complementary thin-film transistor circuit according to the invention.

fig. 3c a fifth embodiment of the complementary thin-film transistor circuit according to the invention.

fig. 3d a variant of the embodiment in fig. fig. 3c,

figs. 4a-4r schematically the process steps in an embodiment of a method according to the present invention,

10 figs. 5a-5d a tri-layer etch process as used with a method according to the present invention.

figs. 6a-6c a back-channel etch process as used with a method according to the present invention.

fig. 7a schematically a section through an inverter realized with the complementary thin-film transistor circuit according to the present invention,

fig. 7b the circuit diagram of the inverter in fig. 7a.

fig. 7c a line drawing based on a microphotograph of the actual inverter in fig. 7a realized in thin film technology.

fig. 8a the voltage transfer curve for an inverter realized as in fig. 7a,

fig. 8b a diagram of the transient current for an inverter realized as in fig. 7a, fig. 9a a line drawing based on a microphotograph of an actual NAND gate realized with complementary thin-film transistor circuits according to the present invention,

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fig. 9b a circuit diagram of the NAND gate in fig. 9a,

25 fig. 9c the output voltage of the NAND gate in fig. 9a,

fig. 10 a line drawing based on a microphotograph of an actual five-stage ring oscillator realized with complementary thin-film transistor circuits according to the present invention,

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fig. 11 the circuit diagram of the ring oscillator in fig. 10,

figs. 12a-12c respectively the gate delay, the power dissipation and the power dissipation product for the ring oscillator in fig. 10 as function of the supply voltage, and

figs. 13a-c respectively the gate delay, the power dissipation and the power dissipation product as function of the supply voltage for an eleven-stage ring oscillator realized with complementary thin-film transistor circuits according to the present invention.

First there shall now be given a discussion of prior art with the above-mentioned US patent No. 5 625 199 (Baumbach & al.) as starting point. Therein is disclosed a complementary circuit with inorganic n-channel thin-film transistor and an organic p-channel thin-film transistor, such as rendered in fig. 1. For both transistors a common gate electrode 2 of metal is provided on a substrate 1. Over the gate electrode is provided a dielectric 3

which forms the gate isolator and which typically is made of a which forms the gate isolator 3 then follows a layer 4 of non-conducting polymer. Over the gate isolator 3 then follows a layer 4 of non-conducting polymer. Over the gate isolator 1 layer of the inorganic undoped amorphous silicon which forms the active layer of the inorganic n-channel transistor. On the a-Si layer 4 is provided a patterned isolation layer 5 which serves to prevent short circuit between the source and drain layer 5 which serves to prevent short circuit between the source and drain layer 5 areas of the n-channel transistor. Over the layers 3, 4 and 5 a further layer of n- amorphous silicon has been deposited and provides electrical contact to of n- amorphous silicon layer 4. The source/drain electrodes 7 are the active amorphous silicon layer 4. The source/drain electrode of the deposited patterned such that the source electrode and drain electrode of the n-channel transistor are not short-circuited. The metal layer 7 is besides n-channel transistors in the circuit patterned such that the n-channel and the p-channel transistors in the circuit are connected. Consequently the layer 7 extends towards the p-channel

patterned such that the Incitation and the parterned such that the Incitation are connected. Consequently the layer 7 extends towards the p-channel are connected. Consequently the layer 7 extends towards the p-channel transistor and forms the source contact therein. Now follows a layer 8 of an isolating material, for instance silicon nitride, polyimide or another dielectric in order to isolate the source/drain electrodes 7 against the active organic in order to isolate the source/drain electrodes 7 against the active organic semiconductor layer 9 which is formed of \alpha-hexathienylene (\alpha-6T) and semiconductor layer 9 which is formed of \alpha-hexathienylene (\alpha-6T) and which for instance may be deposited by vacuum sublimation. Finally, the prior art circuit comprises the drain electrode 10 of the p-channel transistor prior art and and will be connected to the positive supply voltage. This prior art Ag and will be connected to the positive supply voltage. This prior art complementary transistor circuit is then in a final step coated with a

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passivation layer 11. e.g. of silicon nitride or polyimide, to protect the circuit.

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deposited on a substrate and covered by a layer of silicon nitride which forms extends beyond this where it forms n* doped areas for source and drain in the material of the source electrode of the inorganic transistor may be of another electrode is itself then deposited over the active semiconductor material and deposited over the gate isolator such that the source and drain electrodes of the gate isolator. The inorganic active semiconductor material is here shown in the form of hydrogenated amorphous silicon (a-Si:H) and provided such A section through a first embodiment of a complementary transistor circuit that it registers with the gate electrode of the inorganic transistor, but also inorganic transistor. The contact material proper for the drain or source thin-film structure. Over both the inorganic and the organic transistors' metal than the metal in the gate electrode. Correspondingly the contact material for the source and drain electrodes of the organic transistor is the organic transistor in each case are located on the same level in the mutually isolated by a patterned isolation layer of silicon nitride. The electrodes for respectively the inorganic and the organic transistor are according to the present invention is shown in fig. 2a. Separate gate source and drain contacts a double layer of respectively 2 2 2

electrode of organic transistor. The broken re-entrant profile and the isolating transistor is exposed, the isolating double layer in this area in section having provided in the form of a layer over the isolating double layer where this has semiconductor material contacts both the source and the drain electrodes of such that the portion between the source and drain electrodes in the organic polymethylmetacrylate and Novolac photoresist is provided, but patterned semiconductor material optionally may be removed where it covers the a re-entrant profile. The organic active semiconductor material is now double layer provide a secure electrical isolation between the organic the organic transistor and simultaneously also registers with the gate transistor and the inorganic transistor. Of course, the active organic not been removed and in the exposed portion thereof, such that the solating double layer. In fig. 2a it is, however, retained. 30

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It is to be understood that the active inorganic semiconductor material is not restricted to a hydrogenated amorphous silicon, but may well consist of 35

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comprehensive discussion of these materials it shall besides be referred to the polyconjugated organic compounds with suitable properties and be formed by ortho-fused or ortho- and peri-fused aromatic polycyclic hydrocarbons with 4 and T_2 independently represent –H or a lower alkyl and ${f r}$ is an integer which several such. As example of such polyconjugated organic compounds and as have a molecular weight which is not greater than about 2000. For a more to 20 fused rings, polyenes with the formula H-C(T₁)=C(T₂)– H where T₁ Correspondingly the organic active semiconductor material in the organic which includes or consists of phenylene groups which may be substituted, may vary from 8 to 50, as well as conjugated oligomers whose repeating known in the art, it may be mentioned conjugated oligomers, the units of organic semiconductor transistor contain at least 8 conjugated bonds and drain material may also be deposited separately and be different from the polyconjugated compound used as active semiconductor material in the hydrogenated microcrystalline or polycrystalline silicon. The source and transistor is not restricted to pentacene, but may generally be made of channel area, e.g. n* doped microcrystalline hydrogenated silicon. units contain at least a five-link heterocycle. Generally shall a above-mentioned US patent no. 5 347 144 (Garnier & al.). 2 2

material by etching, as such materials usually are damaged or destroyed when they are subjected to common photoresists and chemicals for treatment of the simplified version of the complementary thin-film transistor circuit. In fig. 2b removed such this is shown in fig. 2c. In each case the active semiconductor inorganic transistor. In that connection it shall be remarked that generally it photoresist. However, it has turned out that a water-based etch process with material is removed outside the organic thin-film transistor. The mask layer material in the organic transistor becomes electrically isolated against the semiconductor material in the p-channel transistor may be achieved with a water-based material provides very good results. In the patterning of e.g. of the photoresist may be retained as shown in fig. 2b, but it may also be organic optoelectronic material may e.g polyvinyl alcohol as solvent and As an alternative to the embodiment in fig. 2a. the isolation of the active has been regarded as a problem to remove active organic semiconductor gelatine as photoresist be an advantageous alternative. Besides are both thin-film transistor circuit, whereafter the organic active semiconductor this is shown by providing a photoresist layer over the complementary 8 35 53 2

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particularly printing may in the long run turn out to be both the simplest and photolithography and printing other possible alternatives to etching cheapest

substrate, the gate isolator consists of the same material in both cases and the according to the present invention where an organic thin-film transistor with metal for the source/drain electrode similarly is the same for both transistors. an n-channel organic semiconductor is employed. Fig. 3 shows the simplest embodiment possible, wherein separate gate electrodes are provided on the Fig. 3a shows a section through an organic/inorganic thin-film transistor

and is not as sensitive to external conditions as other organic semiconductor This organic semiconductor shows field-effect mobilities up to $10^{-2}\,\mathrm{cm/Vs}$ complementary ringoscillators", Appl. Phys. Lett., Vol. 74 No. 18 (1999)). As an example of an organic n-channel material may be mentioned copper hexadecafluorophtalocyanine (F16CuPc) (see Y.Y. Lin & al.. "Organic .0

materials of the n-type such as buckminsterfullerene (C60). 2

semiconductor material of the n-type may be combined with one of several copper-hexadecastuorophtalocyanine (F16CuPc) or another organic inorganic p-channel semiconductor materials in order to form the Organic n-channel thin-film transistors based on

complementary thin-film transistor circuit. 2

transistor technology for flat panel displays", Solid-State Electronics, Vol. 34 mobilities of about 5-15 cm²/Vs, but requires a more complicated processing mentioned p-channel amorphous silicon which has field effect mobilities As examples of suitable inorganic semiconductors of the p-type may be comparable with FiaCuPc. or copper-doped polycrystalline germanium pc-Ge:Cu) which in the literature is shown used in combination with polycrystalline thin-film technology (see J. Doutreloigne & al., "The electrical performance of a complementary CdSe:In/Ge:Cu thin film No. 2 (1991)). Polycrystalline germanium has displayed field-effect indium-doped cadmium selenide (Cd-Se:In) in a complementary 8 25

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inorganic transistor, something which may be advantageous, but which is not polymethylmetacrylate and Novolac photoresist such that the portion above also here being broken by a re-entrant profile. The active semiconductor in the n-channel organic semiconductor is exposed, the isolating double layer a necessary condition for using an organic active n-channel semiconductor embodiment in fig. 3b is analog to that in fig. 2a, but with the same metal used for the source and drain electrodes in both transistors. The isolating the n-channel organic transistor will then be isolated from the p-channel Fig. 3b shows an embodiment of the complementary thin-film transistor circuit according to the invention with an n-channel transistor. The double layer may be realized as in fig. 2a. namely consisting of 2

fig. 2b, namely as shown in fig. 3c, where a photoresist is etched and masked n-channel transistor and it is then obtained the variant which is shown in fig also be achieved in corresponding manner as shown for the embodiment in The isolation of the organic active n-channel semiconductor material may such that the n-channel organic active semiconductor is isolated. The etch mask. i.e. the photoresist. may also here be removed from the organic 3d of the embodiment in fig. 3c. 2

echnology be given a description of specific features in the fabrication of the consisting of polymethylmetacrylate (PMMA) and Novolac photoresist which thin-film transistor were deposited by means of thermal evaporation. In order inorganic thin-film transistor. The source and drain electrodes of the organic inorganic a-Si:H thin-film transistor is made in a process which provides an inverted staggered three-layer structure, something which shall be described There shall now with reference to figs. 4a-4r which schematically show the echniques as well as sputtered deposition of source and drain metal for the transistor, in this case pentacene, a re-entrant photoresist profile was used complementary thin-film transistor circuit according to the invention. The circuit. This is a necessary step, as thin-film transistors with pentacene as together forms an isolating double layer in the complementary transistor more closely in the following. The layers of a-Si:H/SiN were deposited process scheme for integrated complementary a-Si:H organic transistor using of plasma-enhanced chemical vapour deposition. The subsequent process step comprises standard lithographic methods and wet etching to isolate the active semiconductor material of the organic thin-film 35 ឧ 25 30

leakage in the pentacene layer, but as pentacene is sensitive to most forms of With the method according to the invention the isolation is achieved during threshold, i.e. a positive voltage must be used on the gate electrode to turn photolitography after the deposition of the organic semiconductive layer. the deposition of the pentacene layer by breaking this over the re-entrant double-layer profile in the organic transistor. The maximum temperature semiconductor of pentacene in the organic transistor in order to prevent chemical processing, it is difficult to achieve isolation with the use of p-channel active semiconductor material usually will have a positive the transistor off. It is hence necessary to isolate an active p-channel which was used during the fabrication was 250°C.

uppermost silicon nitride layer is etched and in the subsequent process step in the lowermost nitride layer by means of a third mask III. The etching itself of photoresist is now patterned with another mask II in order to actively define a fig. 4f the layer of hydrogenated amorphous silicon is etched. In the process shown in fig. 4b. By means of plasma-enhanced chemical vapour deposition, In fig. 4a the gate electrode metal is deposited on the substrate by sputtering a tri-layer structure is thereafter deposited. consisting of a gate isolator $\mathrm{SiN}_{\mathbf{x}}$ however, substantially will be self-explanatory to a person skilled in the art. step shown in fig. 4g a photoresist is patterned for etching of i-stopper and explicitly be discussed with a concrete short reference to figs. 4a-4r which, silicon and finally an isolation layer, once again formed of silicon nitride, over both gate electrodes. thereabove a layer of hydrogenated amorphous Now the process steps for the fabrication of a transistor of this kind shall and then the separate gate electrodes are patterned with a first mask I as the i-stopper and the lowermost silicon nitride layer is shown in fig. 4h. ihin-film transistor with hydrogenated amorphous silicon. In fig. 4e the such as shown in fig. 4c. In the subsequent step shown in fig. 4d a

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from the first metal used in the gate electrodes. In the process step shown in fig. 41 the source/drain metal M2 for the organic transistor was lifted off and chemical vapour deposition and in the subsequent process step in fig. 4j this lift-off of source/drain electrode metal. This is sputtered in the process step as shown in fig. 4k and is denoted with M2 which may be a metal different In order to realize the source and drain areas of the n-channel transistor as shown in fig. 41 n* a-Si:H is now deposited by means of plasma-enhanced takes place by means of a fourth mask IV for patterning a photoresist for

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then follows in the process step shown in fig. 4m an etching of the n layer of hydrogenated amorphous silicon which hence shall provide the source and drain areas of the inorganic transistor.

ig. 4q. Finally is now the organic active semiconductor material deposited in Now follows in the process step shown in fig. 4n a patterning of a photoresist re-entrant broken profiles of the isolating double layer, such this is shown in portion the active p-channel semiconductor material of the organic transistor. transistor appears with source and drain electrodes of the metal M3 provided for lift-off of the metallization of the organic thin-film transistor. This takes isolating double layer is patterned such that the source and drain electrodes place by means of a fifth mask V. A metal layer of a third metal M3 is now now by means of photo-lithography deposited a double layer consisting of thin-film transistor electrically against the inorganic thin-film transistor is the form of pentacene over the whole circuit and provides in the exposed follows the lift-off of this metal layer M3, such that the organic thin-film polymethylmetacrylate PMMA and for instance Novolac photoresist. The in the same level in the thin-film structure. In order to isolate the organic of the metal M3 for the organic thin-film transistor are exposed between deposited over the whole transistor circuit, as shown in fig. 40, and then 2 12

complementary organic thin-film transistor circuit according to the invention It shall be understood that the pentacene layer where it covers the isolating double layer besides may be removed therefrom in a concluding not shown process step. Further may, of course, electrically isolating passivation and planarization layers be deposited over the whole complementary thin-film circuit, such this is known in the art. but not here specifically shown. The now appears substantially as shown in fig. 4r and corresponding to the embodiment shown in fig. 2a.

deposited on the patterned gate electrode. The uppermost silicon nitride layer the source and drain electrodes is patterned and the doped amorphous silicon The tri-layer etch process as used with the present invention and as rendered hydrogenated silicon is deposited all over as shown in fig. 5c. The metal of somewhat greater detail with reference to figs. 5a-5d. In the tri-layer etch tydrogenated amorphous silicon and a further layer of silicon nitride are in the process steps as shown in figs. 4c-h shall now be discussed in process as shown in fig. 5a, a triple layer of silicon nitride, undoped is patterned as shown in fig. 5b and an n* doped layer of amorphous

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the source and drain electrodes must be patterned on the top of the uppermost fig. 5d. As the uppermost silicon nitride layer protects the channel area in the silicon nitride layer which is patterned with the channel length, this requires tri-layer process requires two deposition steps of amorphous silicon and as material over the uppermost silicon nitride layer etched away, as shown in inorganic thin-film transistor, this etch step is not critical. However, the a more aggressive photolithography for a given channel length.

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in the channel area is a critical step. Typically back-channel etching results in hydrogenated amorphous silicon in the channel area is etched away, such this is shown in fig. 6b and fig. 6c respectively. The back-channel etch process is very simple, but the etching of the n⁺ doped hydrogenated amorphous silicon inorganic thin-film transistors with poorer quality than that may be obtained followed by undoped hydrogenated silicon and \mathbf{n}^{\star} doped silicon as well as a further layer of n* doped hydrogenated amorphous silicon. This is shown in The back-channel etch process is shown in fig. 6a-6c. An isolation layer of silicon nitride is deposited over the gate electrode and the substrate, and fig. 6a. The source and drain electrodes are patterned and the doped by using a three-layer etch process.

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invention. Functionally the inverter in fig. 7a corresponds substantially to the electrode contact may then be deposited in the same process step as shown in transistor as well as the inverter gate contact against the inorganic transistor. nverter is based on a p-channel semiconductor material, viz. pentacene, and but is based on the embodiment according to the present invention such this semiconductor material in the inorganic transistor. As the input signal to the complementary transistor circuit according to prior art as rendered in fig. 1, fig. 4a-4b with the use of mask I. As in fig. 2a the isolating double layer of polymethylmetacrylate on Novolac photoresist will isolate both the organic sydrogenated amorphous silicon in doped and undoped form is used as the nverter shall be conveyed to the gate electrodes, there is for this purpose for instance is shown in fig. 2a. As therein the organic transistor of the nverter, be removed. The well-known schematic circuit diagram of the Fig. 7a shows a schematic section through an inverter formed with the provided a gate electrode contact as shown to left in fig. 7a. This gate Besides may also here the pentacene layer which is provided over the solating double layer as well as over the gate electrode contact of the integrated complementary thin-film transistor circuit according to the

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shown by the line drawing in fig. 7c. The organic thin-film transistor is here complementary transistor circuit and a method according to the invention is located at left and the inorganic thin-film transistor in the complementary inverter shown in fig. 7b and an inverter realized with use of a

Fig. 8a shows the voltage transfer curves for different supply voltages for an inverter with a β ratio of 1. The β ratio is here defined by

thin-film transistor circuit at right in fig. 7c.

$$\beta = \frac{(W/L)_{u-N:H}}{W/L_{pertocene}}$$

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the voltage levels of the complementary thin-film transistor circuit according In this regard it shall be remarked that in CMOS circuits both transistors may to the invention. The transition current for the inverter reaches a top near the supply voltage of 20 V. The on voltage of the inverter is equal to the supply voltage and the off voltage is 0 V. This shows the complete maintenance of logic transition voltage and is otherwise very low, such this is evident from - The inverter shows sharp transitions with a gain which exceeds 22 for a sometimes defined as the width/length relationship W/L for the n-channel device divided by the length/width relationship for the p-channel device. be operated both as driver and load. Due to a topological similarity $\boldsymbol{\beta}$ is according to the present invention has a true complementary behaviour. fig. 8b. This shows that the complementary thin-film transistor circuit

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gate is of course obtained, the output of which then becoming the inverted of corresponding Boolean functions be realized with the use of a NAND gate as gate realized by means of a complementary transistor circuit according to the corresponding schematic circuit diagram in fig. 9b. By connecting the output that generally may all logic gates as known in the CMOS technology and the these are shown in fig. 8a. A person skilled in the art will, of course, realize With the complementary thin-film transistor circuit according to the present known in the CMOS-technology. An example of a complementary NANDdifferent input voltages for the NAND gate is shown in fig. 9c and has the same properties as the voltage transfer curves for the simple inverter such invention it is, of course, possible to realize logic gates as otherwise wellof the NAND gate to the inverter shown in fig. 7c a complementary AND the output signal from the NAND gate. The voltage transfer curve for present invention is shown in the line drawing in fig. 9a and the 25 2

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shown in fig. 9a and inverters as shown in fig. 7c. The integrated complementary thin-film transistor circuit according to the invention is generally used for realizing logic gates in complementary thin-film technology.

5 By means of the integrated complementary thin-film circuits ring oscillators were made with respectively 5 and 11 inverter stages and with different β ratios. These ring oscillators show a single gate delay as low as 5 μs, a gate power dissipation less than 0.2 μW per stage and a power delay product as low as 15 pJ. The gate delay decreases fast with the increasing supply voltage, such that high operating frequencies may be obtained with the relatively low supply voltage.

A line drawing of a five-stage ring oscillator is shown in fig. 10 and with the circuit diagram rendered in fig. 11. In addition to the five inverter stages an additional sixth inverter is used for isolating the circuit from the capacity load of an oscilloscope used for measuring the characteristics of the ring oscillator. From the measured oscillation frequency the delay of a single inverter stage can be derived. Fig. 12a shows the single gate delay for the shown five-stage ring oscillator, fig. 12b power dissipation and fig. 12c the power delay product for the same, all figures showing these characteristics for a β ratio of 1/2.

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A ring oscillator with eleven inverter steps is realized in corresponding manner with the use of the integrated complementary thin-film circuit according to the present invention, but not shown herein. Fig. 13a, 13b and 13c, however, show the corresponding characteristics for this eleven-stage ring oscillator as shown in fig. 12a-12c, but with a β ratio of 1/3.

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The methods according to the present invention are simple and hence make it possible to fabricate integrated complementary thin-film transistor circuits according to the invention at low costs. Complementary transistor circuits have an inherent low static power consumption, something which is of importance for applications based on battery power. This makes the complementary thin-film transistor circuit according to the invention applicable in control circuits for liquid crystal displays in portable PCs, so-called "lap-tops" or for low-level implementation such as programmable tags. The circuits according to the invention have high switching amplification and very good maintenance of the logic level in addition to low

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static power consumption. The gate delay in the transistor circuits fabricated according to the invention measured by means of ring oscillators is as mentioned as low as 5µs, the fastest speed up to now obtained with circuits which use organic transistors.

The hybrid integrated complementary thin-film technology, wherein the organic transistor may be an n-channel transistor and the organic transistor a p-channel transistor or vice versa, is of course, not restricted to use of the active semiconductor materials as mentioned in the exemplary embodiments. The on-going development of suitable organic as well as inorganic semiconductor materials makes it probable that in the future both n- as well as p-channel active organic semiconductor materials and correspondingly n- as well as p-channel inorganic active semiconductor materials with further improved properties may be employed. Composite inorganic semiconductor compounds may be of interest and the same applies to single crystal silicon, while on the other hand gallium arsenide for the time being appears less probable. but shall in no way be excluded in future hybrid complementary thin-film transistor circuits of the kind disclosed herein.

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CLAIMS

- I. An integrated inorganic/organic complementary thin-film transistor circuit comprising a first and a second transistor which are operatively connected and provided on a common substrate, wherein the first transistor is an inorganic thin-film transistor and the second transistor an organic thin-film transistor, and wherein the complementary thin-film transistor circuit forms a multilayer thin-film structure, characterized in that the inorganic thin-film transistor is an n-channel transistor and that the organic thin-film transistor is a p-channel transistor, or vice versa, the
 - organic active transistor material in each case being respectively a p-channel organic semiconductor material or an n-channel organic semiconductor material, that separate gate electrodes are provided for each of the transistors, that the organic active semiconductor in an organic p-channel transistor in
 - transistor, and transistor, and transistor and transistor and transistor and transistor and that the organic active semiconductor in an organic n-channel transistor optionally is provided electrically isolated from the inorganic p-channel
- A complementary thin-film transistor circuit according to claim 1,
 characterized in that the inorganic active semiconductor material is selected among hydrogenated amorphous silicon (a-Si:H), hydrogenated or unhydrogenated microcrystalline silicon (μc-Si:H;μc-Si), hydrogenated or unhydrogenated polycrystalline silicon (pc-Si:H;μc-Si), single crystal silicon,
 - unhydrogenated polycrystalline stition (pc-5t.rt,pc-5t), stingic crystal stiroct, copper-doped polycrystalline germanium (pc-Ge:Cu), cadmium selenide (CdSe), cadmium telluride (CdTe), or composite inorganic semiconductors based on said materials, possibly in single crystal form.
- A complementary thin-film transistor circuit according to claim 2 wherein the inorganic transistor is an n-channel transistor,
 characterized in that the inorganic active semiconductor material is hydrogenated amorphous silicon (a-Si:H).
- 4. A complementary thin-film transistor circuit according to claim 2, wherein the inorganic transistor is a p-channel transistor, characterized in that the inorganic active semiconductor material is a

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p-channel silicon material, particularly p-channel hydrogenated amorphous silicon (a-Si:H).

5. A complementary thin-film transistor circuit according to claim 1, characterized in that the active semiconductor material in the organic thin-film transistor comprises at least one polyconjugated organic compound

with a specific molecular weight.

- A complementary thin-film transistor circuit according to claim 5, characterized in that the polyconjugated organic compound or compounds are selected among conjugated oligomers, polycyclic aromatic hydrocarbons,
 - 10 particularly polyacenes, or polyenes.
- A complementary thin-film transistor circuit according to claim 6, wherein the organic thin-film transistor is a p-channel transistor, characterized in that the organic semiconductor material is pentacene.
- 8. A complementary thin-film transistor circuit according to claim 1, wherein the organic thin-film transistor is an n-channel transistor, characterized in that the organic active semiconductor material is copper hexadecafluorophtalocyanide (F₁₆CuPc).
- 9. A complementary thin-film transistor circuit according to claim 1, characterized in that the source electrode and the drain electrode of the organic thin-film transistor are provided in one and the same level in the thin-film structure of the organic thin-film transistor.
- A method for fabricating an integrated inorganic/organic complementary thin-film transistor circuit comprising a first and a second transistor which are operatively connected and provided on a common substrate, wherein the first transistor is an inorganic thin-film transistor and the second transistor a organic thin-film transistor, and wherein the complementary thin-film transistor circuit forms a multilayer thin-film structure with successively deposited and patterned thin-film layers, characterized by forming the inorganic thin-film transistor as an n-channel
- characterized by forming the morganic unit-tituin transistor as an in-channel transistor by transistor and the organic thin-film transistor as a p-channel transistor by depositing respectively an n-channel inorganic active semiconductor material and a p-channel organic active semiconductor material or correspondingly forming the organic thin-film transistor as an n-channel transistor and the inorganic thin-film transistor as a p-channel transistor by depositing

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respectively an n-channel organic active semiconductor material and a p-channel inorganic active semiconductor material, depositing separate gate electrodes for respectively the first and the second transistor on a common substrate, depositing material for the source electrode and the drain electrode of the organic thin-film transistor on the same level in the thin-film structure of the organic thin-film transistor and in each case providing the organic active semiconductor material in an organic p-channel transistor electrically isolated from the inorganic n-channel transistor and optionally providing the organic active semiconductive material in an organic n-channel transistor electrically isolated from the inorganic p-channel transistor.

11. A method for fabricating an inorganic/organic complementary thin-film transistor circuit comprising a first and a second transistor which are operatively connected and provided on a common substrate, wherein the first transistor is an inorganic thin-film transistor and the second transistor an organic thin-film transistor, wherein the complementary thin-film transistor circuit forms a multilayer thin-film structure with successively deposited and patterned thin-film layers, and wherein the method is characterized by comprising steps for depositing separate gate electrodes of a first metal for each of the two transistors on a common substrate,

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depositing separate inorganic isolators of silicon nitride (SiN_x) over each gate electrode, depositing an inorganic active semiconductor in the form of hydrogenated amorphous silicon (a-Si:H) above one of the gate electrodes which thus

forms the gate electrode of the first transistor, depositing and patterning an a doped layer of either hydrogenated amorphous silicon (n*a-Si:H) or hydrogenated microcrystalline silicon (n*µc-Si:H) or hydrogenated polycrystalline silicon (n*pc-Si:H) as source and drain contacts for the first transistor, depositing and patterning the source and drain electrodes of the first transistor in form of a second metal over the source and drain contacts thereof, depositing and patterning the source and drain electrodes for the

thereof, depositing and patterning the source and drain electrodes for the second transistor in the form of a third metal in the same layer level in the thin-film structure, forming an isolating double layer over the whole organic thin-film transistor and patterning this such that the source and drain electrodes and the gate isolator in the second transistor become exposed, whereafter a layer of pentacene is deposited above the isolating double layer and the exposed portion of the second transistor, the pentacene layer in the exposed portion forming the active semiconductor material of the organic

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thin-film transistor and being provided electrically isolated against the additional pentacene layer broken by a re-entrant edge of the profile of the isolating double layer.

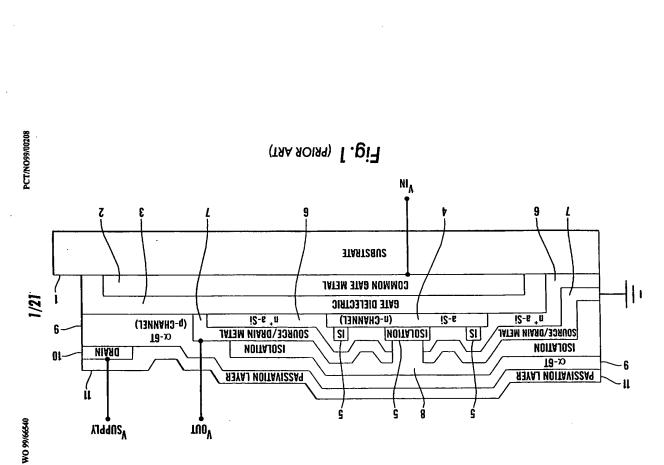
- 12. A method according to claim 11, characterized by realizing the steps for forming the inorganic thin-film transistor in a tri-layer process which forms an inverted staggered tri-layer structure.
- 13. A method according to claim 11, characterized by realizing the steps forming the inorganic thin-film transistor in a back-channel etch process.
- 14. A method according to claim 11, characterized by isolating the active semiconductor in the form of pentacene in the organic thin-film transistor by a re-entrant profile of a broken double layer of polymethylmetacrylate (PMMA) and Novolac photoresist.
- A method according to claim 11, characterized by evaporating gold thermally for forming the source and drain electrodes of the organic thin-film transistor.

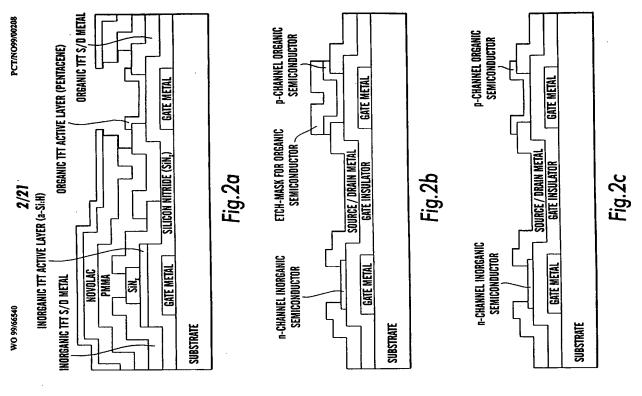
12

16. A method according to claim 11. characterized by optionally removing the pentacene layer which has been deposited over the isolating double layer.

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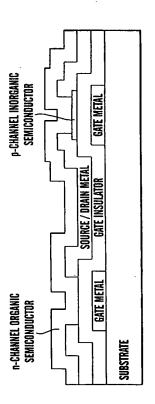


Fig.3a

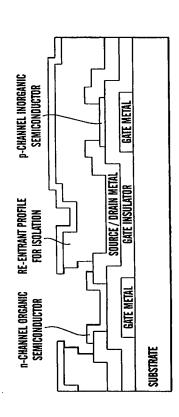
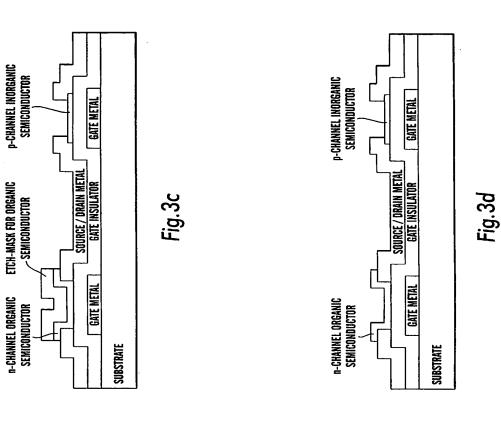


Fig.3b





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SPUTTER OF GATE METAL.

GATE METAL. Substrate

Fig.4a

DEFINITION OF GATE METAL PATTERN (MASK I):

SUBSTRATE

Fig.4b

PECVO OF TRI-LAYER.

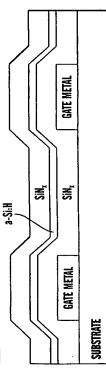


Fig.4c

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PATTERING OF PHOTORESIST FOR ACTIVE DEFINITION OF a-Si-H TFTS (MASK II).

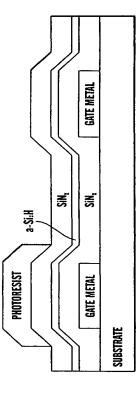


Fig.4d

ETCHING OF TOP NITRIDE LAYER.

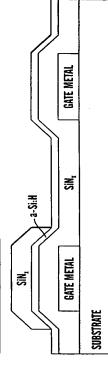


Fig.4e

ETCHING OF a-Si:H LAYER:

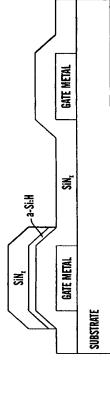


Fig.4f

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PATTERNING OF PR FOR ETCH OF 1-STOPPER AND BOTTOM NITRIDE LAYER (MASK III);

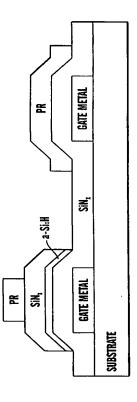


Fig.4g

ETCHING OF 1-STOPPER AND BOTTOM NITRIDE LAYER:

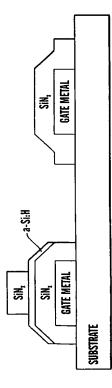


Fig.4h

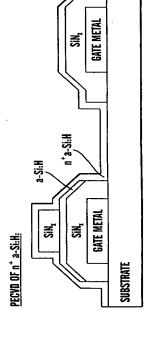


Fig.4i

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PATTERNING OF PR FOR LIFTOFF (MASK IV).

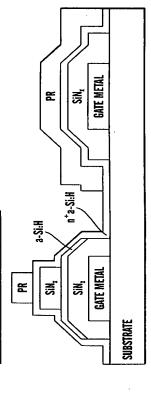


Fig.4j

SPUTTERING OF SOURCE / DRAIN METAL OF A-SI;H TFTs.

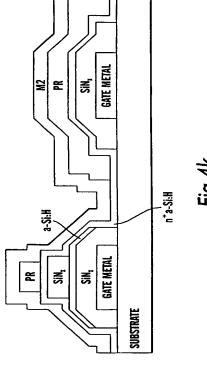
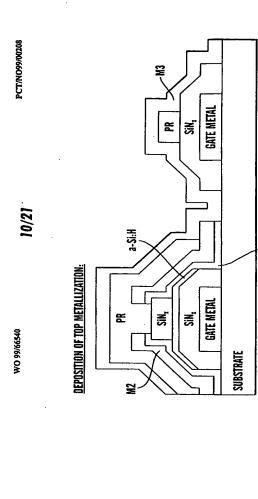


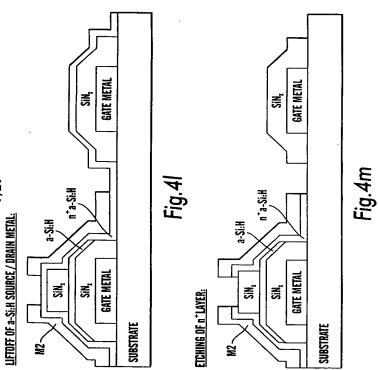
Fig.4k



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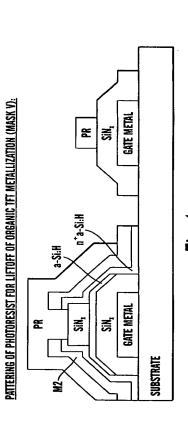


Fig.4n

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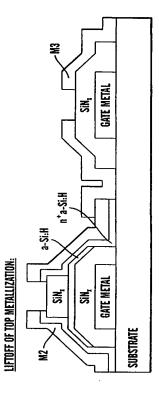
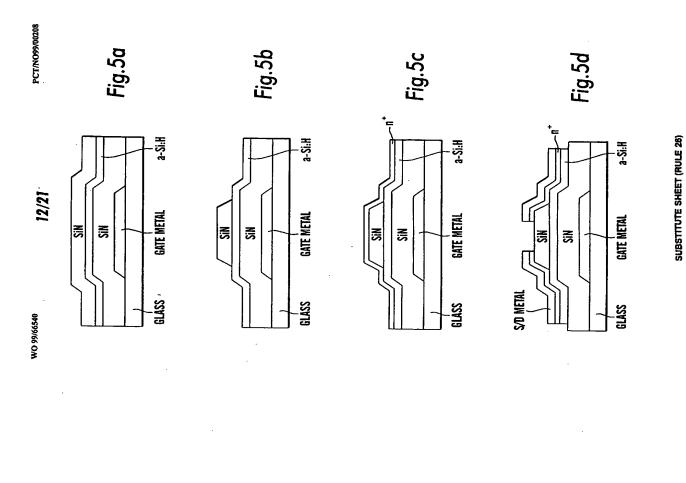


Fig.40

n⁺a-Si.H

Fig.4p



PENTACENE

a-Si:H

DEPOSITION OF PENTACENE ORGANIC SEMICONDUCTOR:

GATE METAL

GATE METAL

SUBSTRATE

Sik

S,

E

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DOUBLE LAYER LITHOGRAPHY FOR ISOLATION:

GATE METAL

GATE METAL

SUBSTRATE

Si.

Fig.4q

n*a-Si:H

SiN

PR

Six

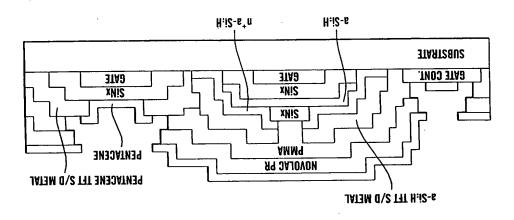
a-Si:H

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Fig.4r

n⁺a-Si:H





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GATE METAL

Sis

GATE METAL S

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a-Si:H

GATE METAL

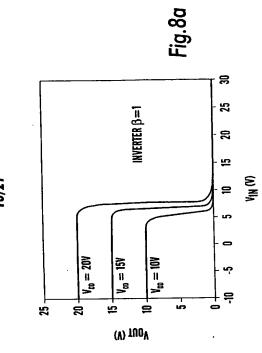
S.



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VOLTAGE TRANSFER CURVE OF a-Si.H / PENTACENE INVERTER

VSS VSS

×

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Fig.7b

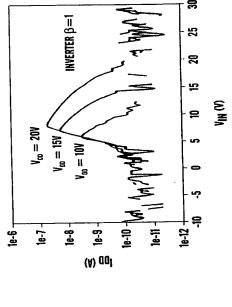


Fig.8b

TRANSIENT CURRENT OF a-Si:H / PENTACENE INVERTER

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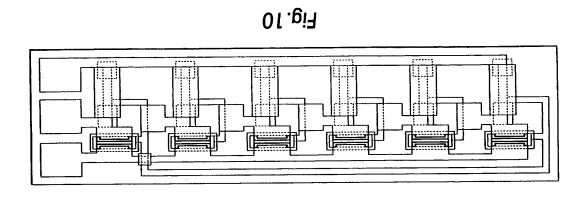
Fig./c

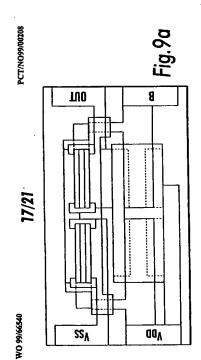
a-Si:H TFT

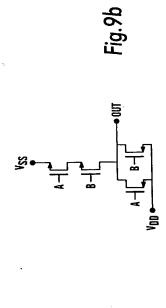
PENTACENE TFT

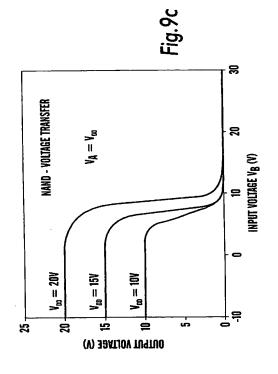
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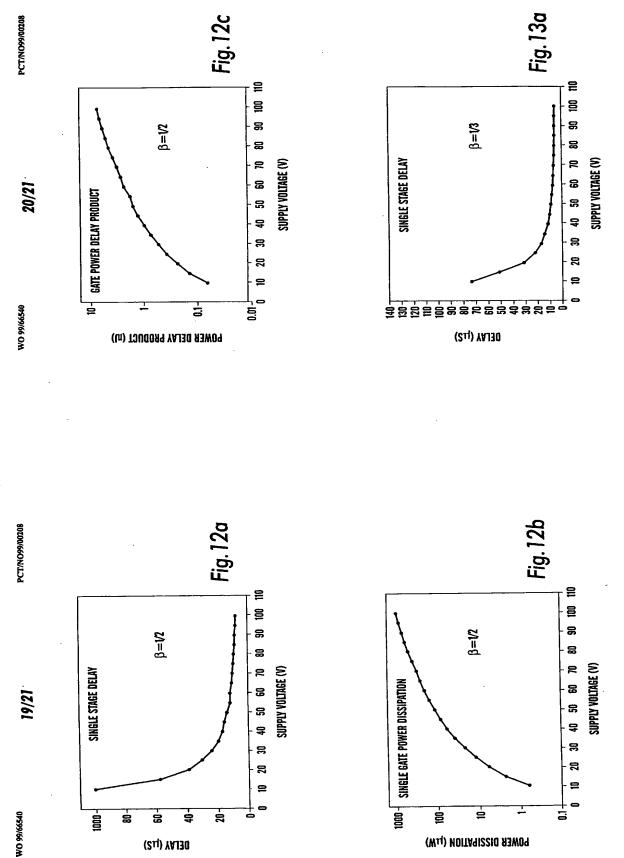








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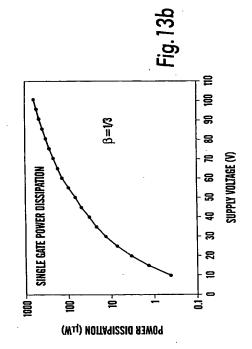


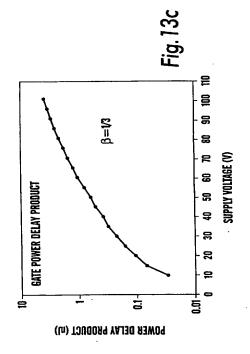
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INTERNATIONAL SEARCH REPORT

International application No. PCT/NO 99/00208

V. CLAS	CLASSIFICATION OF SUBJECT MATTIER	
According 1	IPC7: H01L 29/786, H01L 51/40 International plant Chedication (IPC) or to both national chastification and IPC Figure to a security.	
Minimum d	Minimum documentation gearched (classification system fullowed by classification symbols)	
IPC7: H01L	НОІГ	
Documenta	Documentation searched other than minimum documentation to the extent that such documents are included in the fields rearched	d in the fields rearched
SE,DK,	SE,DK,FI,NO classes as above	
Electronic	Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)	irch terms used)
c. Docu	DOCUMENTS CONSIDERED TO BE RELEVANT	
Category*	Giation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
×	US 5612228 A (CHAN-LONG SHIEH ET AL), 18 March 1997 (18.03.97), see the whole document	1-4,9-10
>		5-7,11,15
⋖		8,12-14,16
	ŀ	
>	EP 0786820 A2 (MOTOROLA, INC.), 30 July 1997 (30.07.97), see the whole document	5-7,11
<		1-4,8-10, 12-16
	1	
K Furd	Further documents are listed in the continuation of flox C. X See patent family mutex.	nex.
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International application No. PCT/NO 99/00208			Relevant to claim No.	5-6,15	1-4,7-14,16	7,11	1-6,8-10, 12-16									
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		C (Contin	Category*	*	∢	: ~	⋖	•								

International application No.	PCT/NO 99/00208
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-		NONE	유	80E	옷뚠	윤육		
	Publeation date	18/03/97	30/07/97	13/09/94		29/04/97		
		V	¥2	⋖		¥		
	Patent document cited in search report	US 5612228 A	0786820 A2	5347144		5625199		
	P. Cited	SD	£	S		Sn		

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